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AN EXPERIMENTAL STUDY OF POWER TRANSISTORS
AS SWITCHING ELEMENTS IN DC
MOTOR RELAY SERVOS
RICHARD G. THOMSON

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THESIS

AN EXPERIMENTAL STUDY OF
POWER TRANSISTORS AS SWITCHING ELEMENTS IN
DC MOTOR RELAY SERVOS

Richard G. Thomson

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DC MOTOR RELAY SERVOS

by

Richard G. Thomson
//
Lieutenant Commander, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

The use of magnetic relays as switching elements in relay servo systems entails certain disadvantages which can be decreased in severity or completely eliminated by the use of transistor switches. Such disadvantages are relay dead zone, hysteresis loops, contact arcing and mechanical failure.

In this paper the use of power transistors as switching elements for DC servo motors is examined. Switching circuits and criteria for use in such are given. Advantages and disadvantages of the use of transistors in place of magnetic relays is discussed. It is shown that the transistor switching method is naturally suited to and automatically affords dual mode operation of the servo motor.

The subject for this paper was suggested by Professor G. J. Thaler of the Electrical Engineering Department, U. S. Naval Postgraduate School, to whom the author wishes to express his appreciation for the assistance and guidance offered him during the course of this study.

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TABLE OF SYMBOLS

Symbol	Definition	Units
BV_{ce}	Collector-Emitter Breakdown Voltage	Volts
h	Tachometer Feedback Constant	Volts/Deg/Sec
h_{fe}	Transistor Forward Current Gain	Amp/Amp
I_a	Armature Current	
I_b	Base Current	
I_c	Collector Current	
I_f	Field Current	
K_a	Amplifier Transconductance	Amp/Volt
K_p	Potentiometer Gain Constant	Volt/Deg
P_c	Allowable Collector Power Dissipation	Watt
	Gear Train Ratio, Output to Input	

1. Introduction.

Relay operated feedback control systems offer the advantage of a relatively low-cost and simple method of automatic control, one capable of handling relatively large amounts of power. Because of the discontinuous nature of this type of servo system linear analysis techniques were not applicable. The non-linear system was subject to limit cycles and a dependence of the output response on the input signal both in magnitude and type, i.e. step, ramp, periodic or random input. Optimum relay servo response theory evolved aimed at determining the necessary switching criteria for optimum, stable response. Since the optimum switching boundary on the phase plane is in general another non-linear function special compensation techniques were necessary to enable the relay servo to achieve deadbeat response to different sized inputs (speaking of step inputs only). This dependence of the switching boundary on input signal magnitude lead in general to position errors about the origin of the phase plane and, depending upon factors such as relay dead zone, hysteresis, system damping etc., the system might or might not go into limit cycle operation because of this switching error. To prevent this type of instability the idea of dual mode operation was conceived whereby a linear or other than torque-saturated region was caused to exist around the origin of the phase plane. The additional compensation devices serve only to detract from the very attractiveness of the relay servo system, namely its low cost and simplicity.

In addition to the switching difficulties described use of contractor type relays in interrupting inductive loads leads to contact arcing and pitting (severe at low atmospheric pressures) and eventual relay failure.

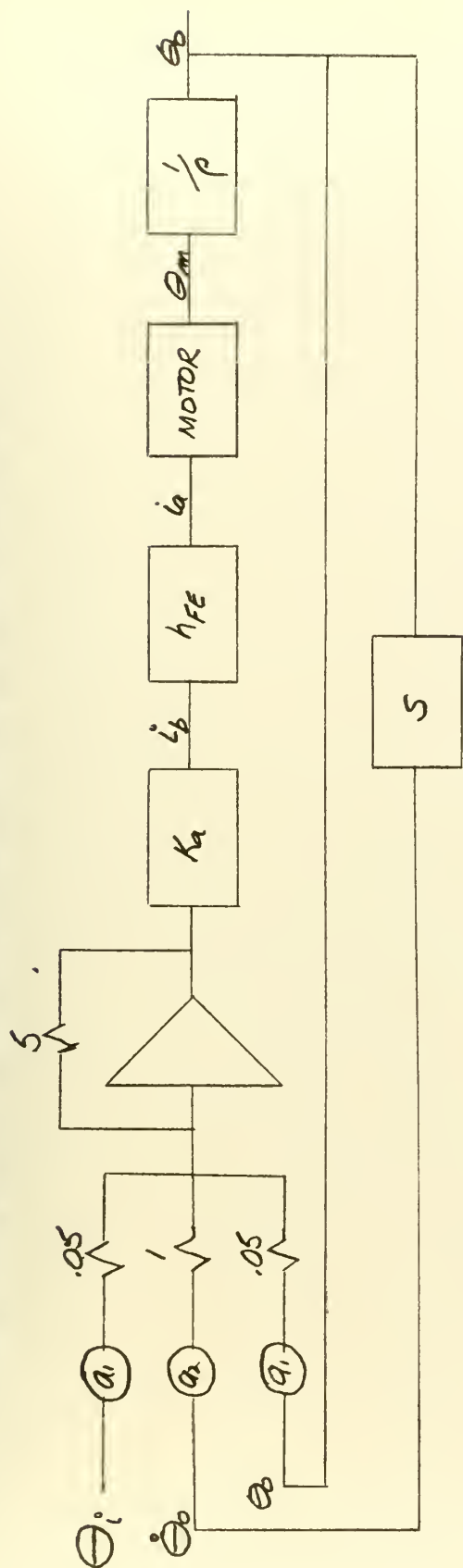
The advent of power transistors capable of sustaining large current loads continuously led to the possibility of replacing the mechanical

switch of the relay servo with one with no moving parts. It also seemed possible that the transistor, which when operated as a saturated amplifier acts as a variable resistance, might be capable of providing dual mode operation without the addition of extra complicating circuitry or linear amplifiers.

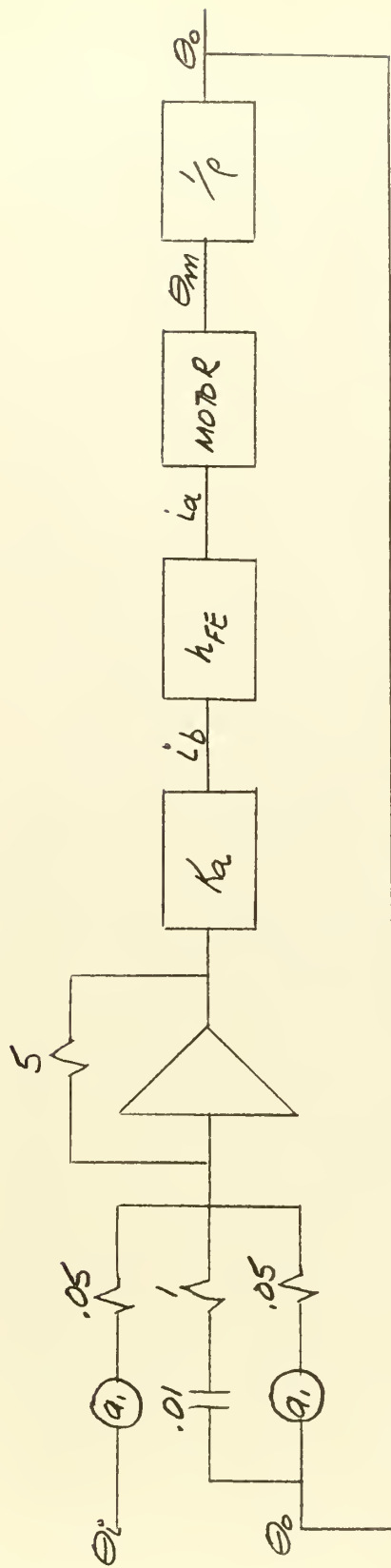
In this study three representative power transistors were used. The purpose of the study was not only to evaluate transistors as to their ability to replace magnetic relays as switches, but also, if the first objective seemed feasible, to determine those transistor characteristics which were important to practical design and which could control dual mode operation.

2. The Experimental Systems.

The servo system used in the experiment was driven by a 28 volt DC 0.4 ampere split field series Oster motor. The gear ratio between input and output was 236:1. ($\frac{\omega_M}{\omega_o} = \frac{1}{p} = 236$). A Philbrick K2W operational amplifier was used to sum the input signals. The output of the K2W was amplified to drive the transistors which operated the motor. Block diagrams of the experimental systems are shown in Fig. 1. Tachometer feedback when used was obtained from an Electric Indicator Co. type FD-88 110 volt DC generator driven by the gear train and having the same gear ratio input to output as the motor. This system is shown in Fig. 1(a). An Error rate control signal, when used, was obtained by sending the position error signal through a lead network to the summing amplifier. This is the system shown in Fig. 1(b). The error signal was obtained from a conventional two potentiometer system one potentiometer of which served as a reference for the other which was driven by the output shaft. The input signal voltage was variously obtained from a Hewlett-Packard low frequency function generator or from a regulated



a) System Utilizing Tachometer Feedback



b) System Utilizing Error Rate Control

Figure 1

DC power supply.

The switching arrangement for the split field series motor is shown in Fig. 2. In this configuration two power transistors are connected in a common-emitter, essentially push-pull, arrangement. A positive input signal (A with respect to B) causes the lower transistor, S2, to conduct. Current flows through the clockwise field winding and the armature toward the emitter causing clockwise rotation. A negative input signal causes S1 to conduct and the counter-clockwise field winding to be activated. For no input signal neither transistor conducts and only leakage current flows as is discussed subsequently.

3. Operation of the Transistor as a Switch.

The transistor operated as a switch in the common-emitter configuration is really a variable resistance, collector to emitter, the amount of resistance being controlled by the base current, I_b . The circuit of Fig. 2 is unbiased so that the collector emitter resistance at zero signal is the "off" resistance of the switch. The "on" condition of the switch is when the transistor is saturated by a base current greater than some minimum value. The amount of current necessary to turn the switch on and its resistance when on is to some degree a function of the load in the collector circuit but is mainly dependent on the characteristics of the transistor itself. The collector-emitter resistance for the three transistors tested versus base (signal) current is shown in Fig. 3. The off resistance is typically thousands of ohms and the on resistance one to one and a half ohms.

The diodes D1 and D2 of Fig. 2 improve the efficiency of the circuit by shunting the resistor R on the switch not conducting. The resistors are

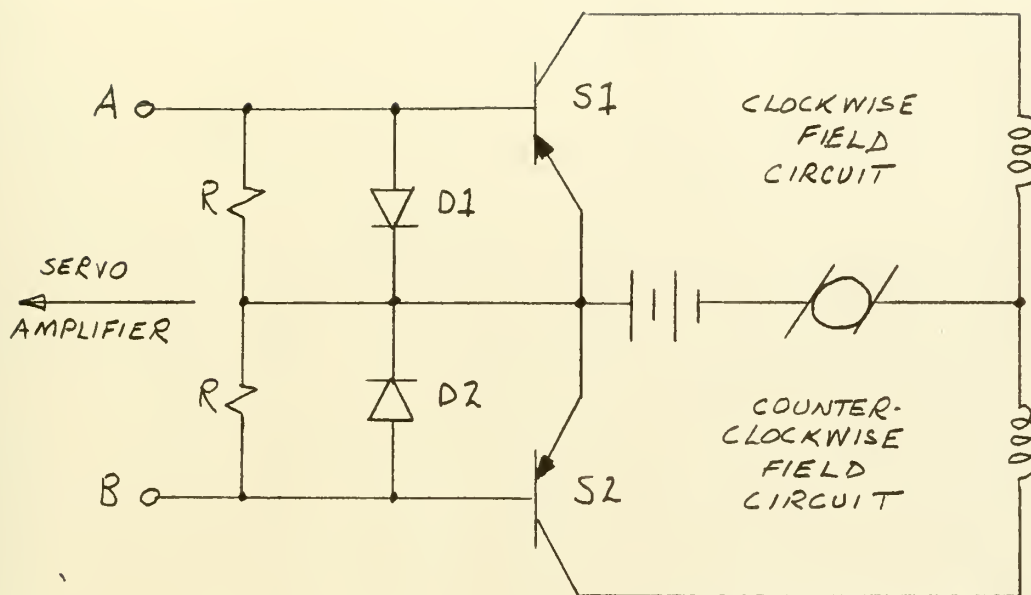
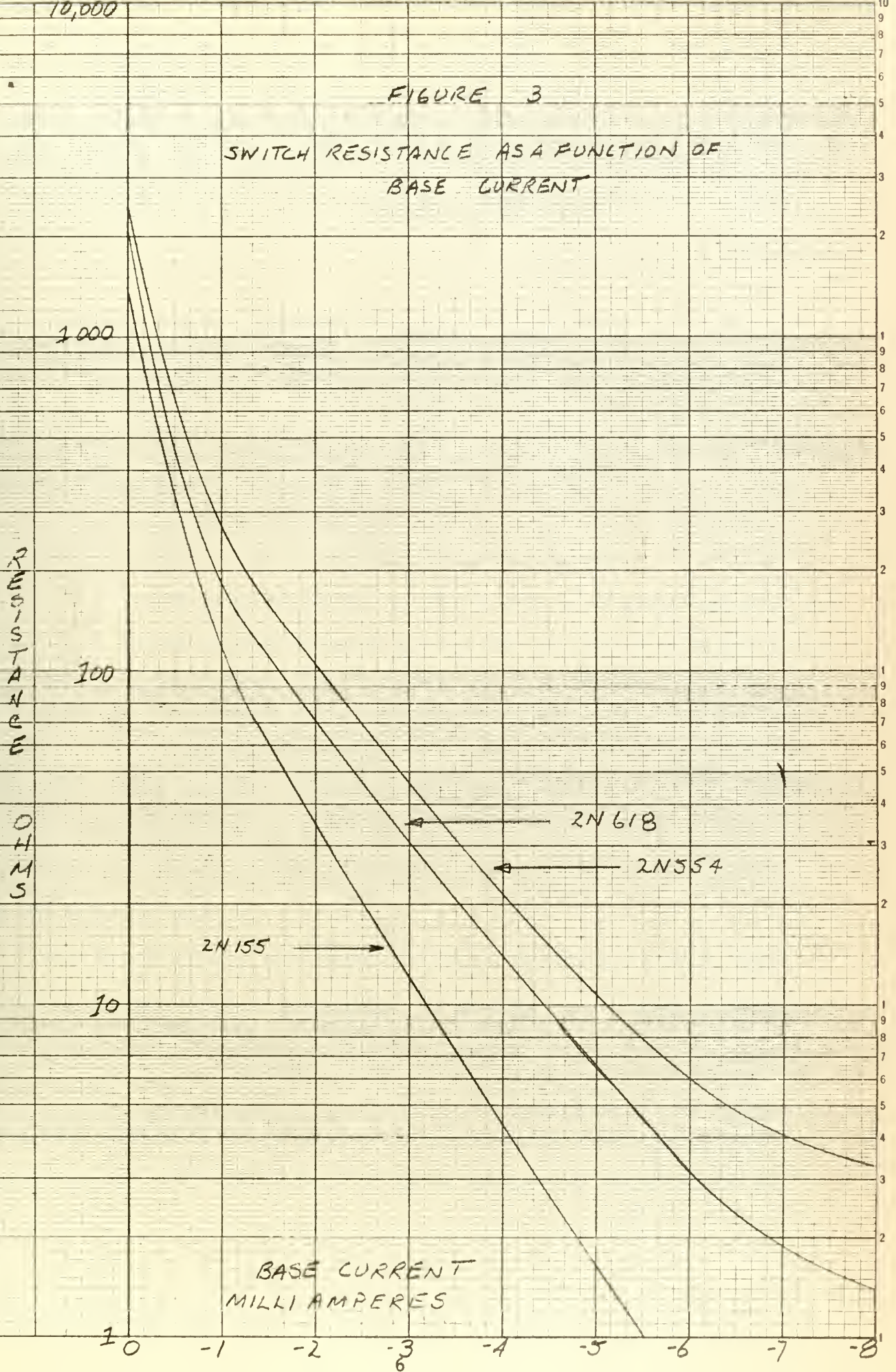


Figure 2
Switching Circuit For DC Series Motor

FIGURE 3

SWITCH RESISTANCE AS A FUNCTION OF
BASE CURRENT



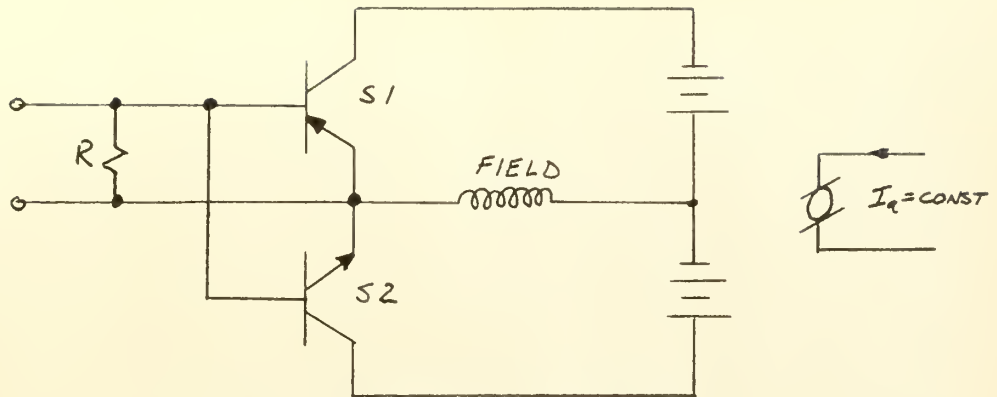
for the purpose of impedance matching and to reduce the zero signal leakage current as discussed subsequently in the section on Design Criteria. The small forward voltage drop across the diode (.18 volt) positively biases the non-conducting switch off raising its resistance by an order of magnitude.

4. Switching Circuits for DC Shunt Motors.

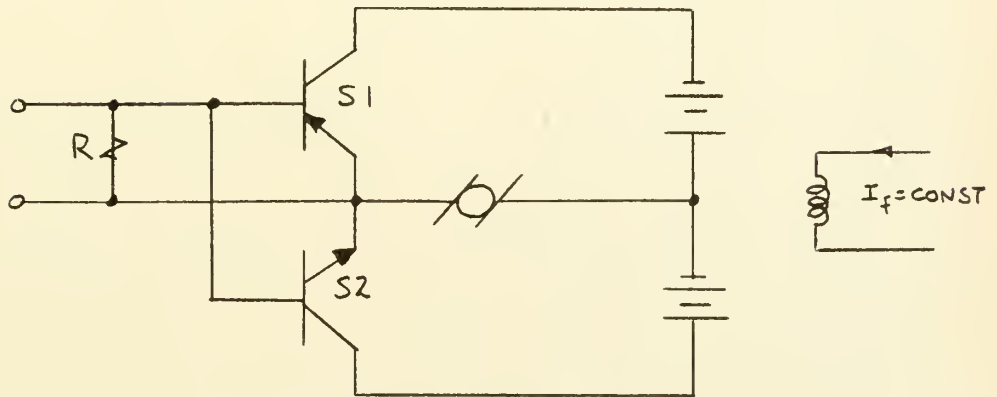
The circuit diagrams of Fig. 4 would be used in transistor switching of DC shunt motors. Circuits 4(a) and 4(b) utilize complimentary PNP and NPN transistors and were not tested because the NPN types were not able to be procured. Fig. 4(a) shows the switch circuit for constant armature current and Fig. 4(b) the circuit for constant field current.

With the same polarity signal applied to both bases simultaneously, and because of the use of complimentary transistors, one switch is turned on and the other turned off. Operation is otherwise similar to the series motor circuit. In the shunt motor circuits of Fig. 4 the bases are not shunted by diodes. Since only one impedance matching resistor is required no power is being needlessly dissipated in the resistance of the off switch as in the series circuit. In this configuration the off switch has a resistance in the kilohm range.

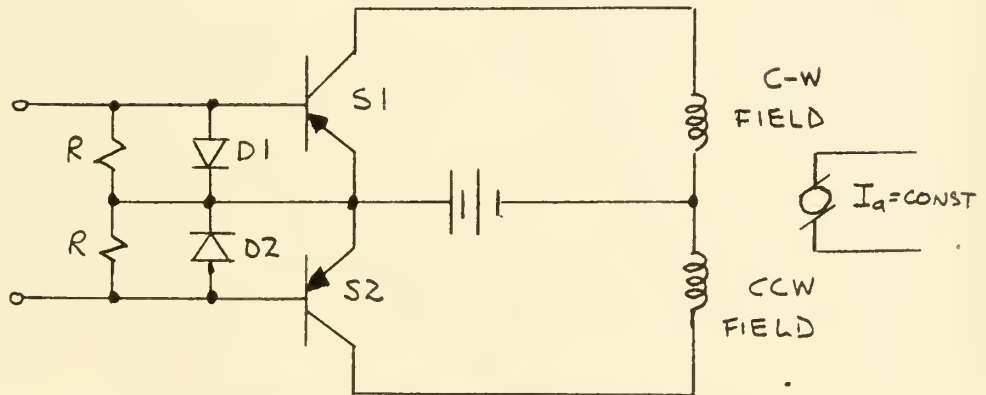
The circuit of Fig. 4(c) would be used in switching the split field constant armature current shunt motor. A separate power supply normally supplies the armature though it could be connected directly across the field supply. The switching circuit is identical to that of Fig. 2 except for the removal of the armature from its series connection in the common branch. With this circuit differential control of the fields can be obtained by suitable biasing of the transistor amplifiers.



a) Constant Armature Current



b) Constant Field Current



c) Constant Armature Current - Split Field

Switching Circuits For DC Shunt Motors

Figure 4

5. Measurements of Switching Characteristics.

Behavior of the transistors as switches was first evaluated. In the normal relay servo measurements of pull-in and drop-out voltage (or current) levels for the relay are generally made for the purpose of determining the relay dead zone and hysteresis loops. Similar measurements were made for the transistors. As noted earlier the transistor switch is a variable resistance the amount of resistance being controlled by the base current. Depending upon the forward current gain h_{fe} of the device the transistor can be saturated with a fixed minimum amount of base current, This amount of current, for a properly impedance-matched circuit, is the maximum which the servo amplifier must supply. If the forward current gain is 100, for example, and the maximum armature current one ampere, then 10 milliamperes is required to fully turn on the switch. Assuming that the amplifier can supply this minimum current, then the rate at which base current and therefore collector current changes with respect to the error signal defines operation in the intermediate region which is neither on or off. From the block diagram of the system, Fig. 1(a), for no tachometer feedback

$$(1) \quad I_f = K_a K_p h_{FE} (\Theta_i - \Theta_o)$$

From the assumption above, K_a can be considered a constant meaning that the collector (armature) current is a direct function of the potentiometer gain constant and forward current gain. If each of these variables has a linear region then the product of the three in the equation above will be constant and a linear relationship between current and error signal can exist.

Tests to determine the gain constants were made. The value of K_p which is fixed by the voltage on the error detectors and the summing and feedback resistances of the operational amplifier was not measured because

of the simplicity of its calculation. A measurement of base current vs output of the summing amplifier was made and is shown in Fig. 5. The slope of this curve, which is very nearly constant over the operating range, is K_a and is taken as 0.807 ma/volt. For the three transistors tested measurements of collector (armature) current vs base current were made with the motor in the circuit and the rotor blocked. These curves are shown in Fig. 6. The slope from a point on the curve to the origin is h_{fe} .

Combining the three constants results in the actual desired curve of the controlled quantity, the collector current as a function of error angle. Fig. 7 shows experimental results of armature current versus error for the three transistors measured at the same potentiometer constant. As would be expected from examination of Fig. 6 the 2N155 saturates before the 2N618 which in turn saturates before the 2N554. To illustrate the effect of potentiometer constant, Fig. 8 shows curves of current vs error for the 2N618 for various values of K_p . Since all three constants are, in fact, constant simultaneously over a region between the on and off positions of the switch a well defined linear region of operation results. As seen from Figs. 7 and 8 the width of the linear region can be independently controlled by both K_p and h_{fe} . All curves pass through the origin or zero error position.

Since the interesting feature of a relay operated servo is its torque saturated operation the current-error curves of Figs. 7 and 8 should be transformed to torque-error curves.

For the DC shunt motor with constant field developed torque is directly proportional to armature current. For a constant armature current motor the torque relationship is also proportional to a first approximation

Experimental Curve To Determine Amplifier Gain Constant

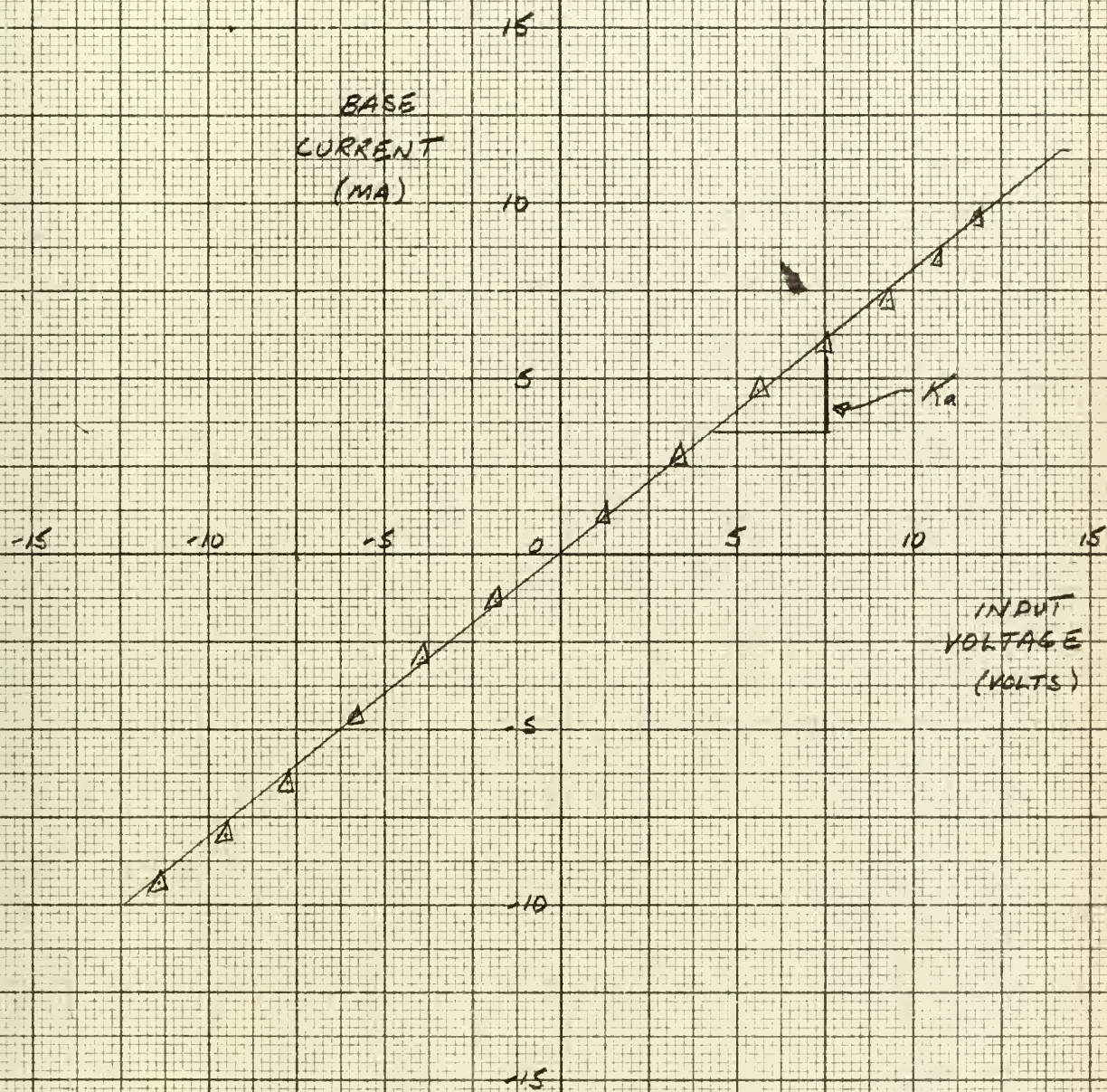
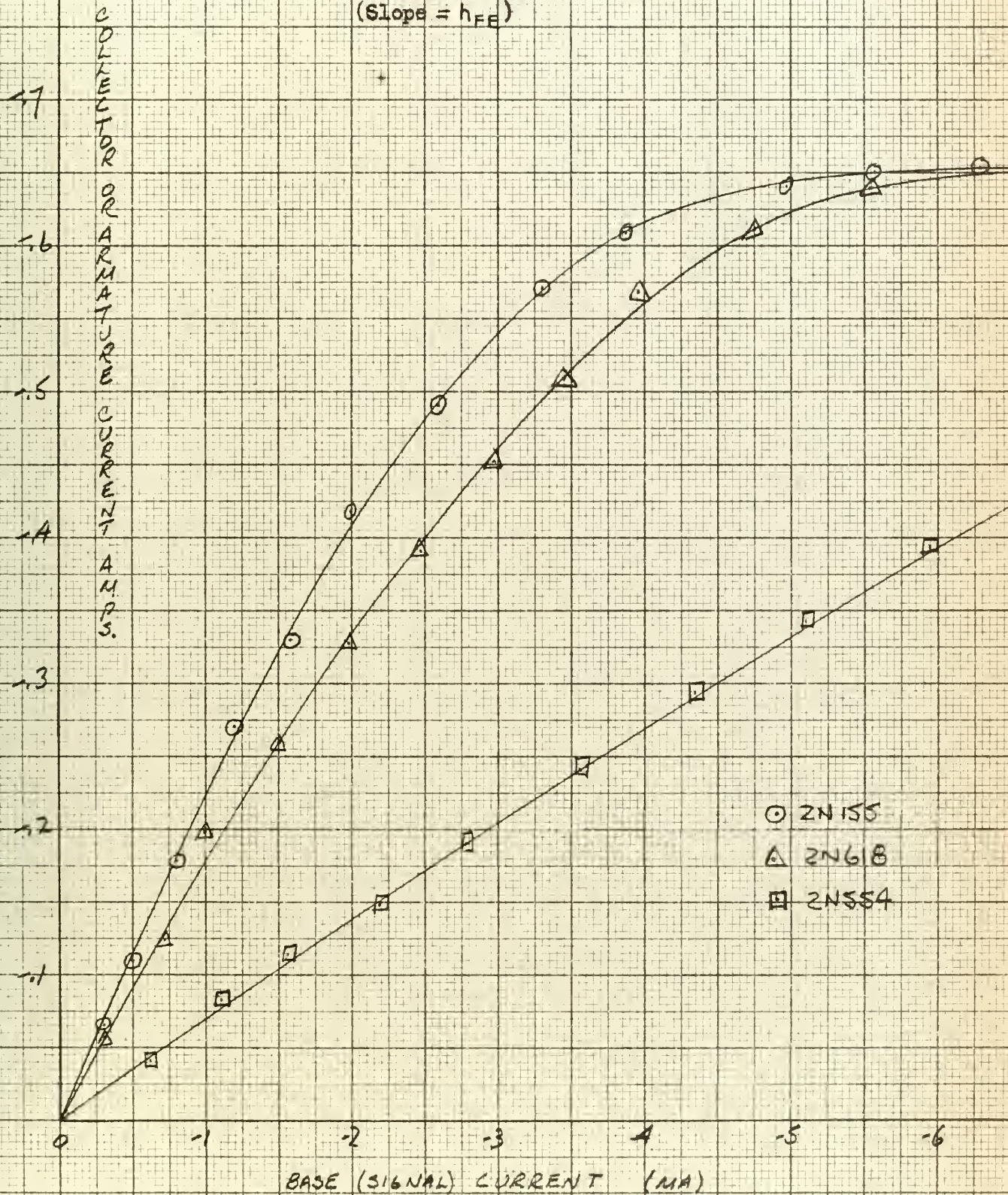


Figure 5

Figure 6

Collector-Base Current
Characteristics
(Slope = h_{FE})



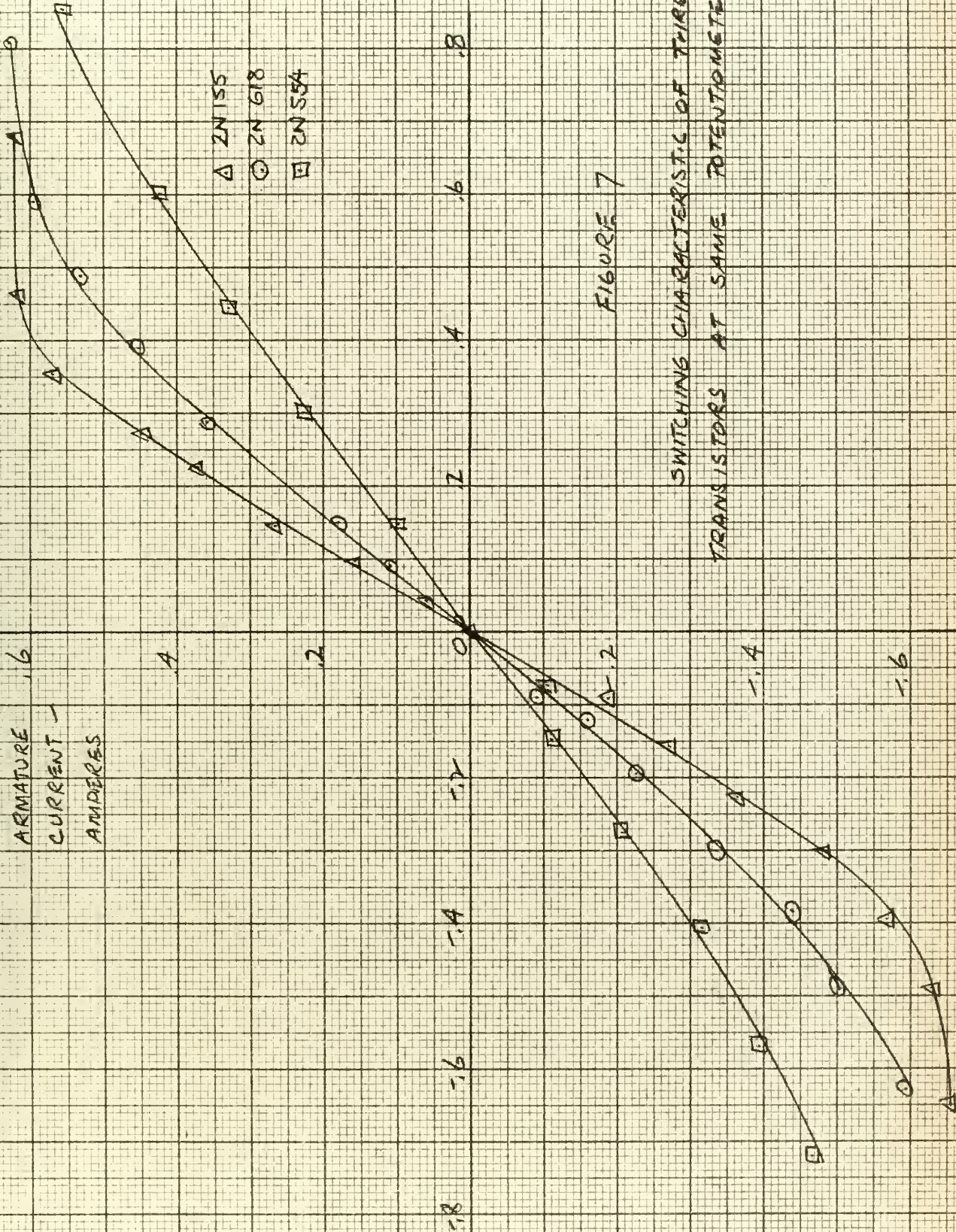
ARMATURE
CURRENT -
AMPERES

ERROR -
DEGREES

△ 2N155
○ 2N618
□ 2N554

FIGURE 7

SWITCHING CHARACTERISTICS OF THREE
TRANSISTORS AT SAME POTENTIOMETER CONSTANT



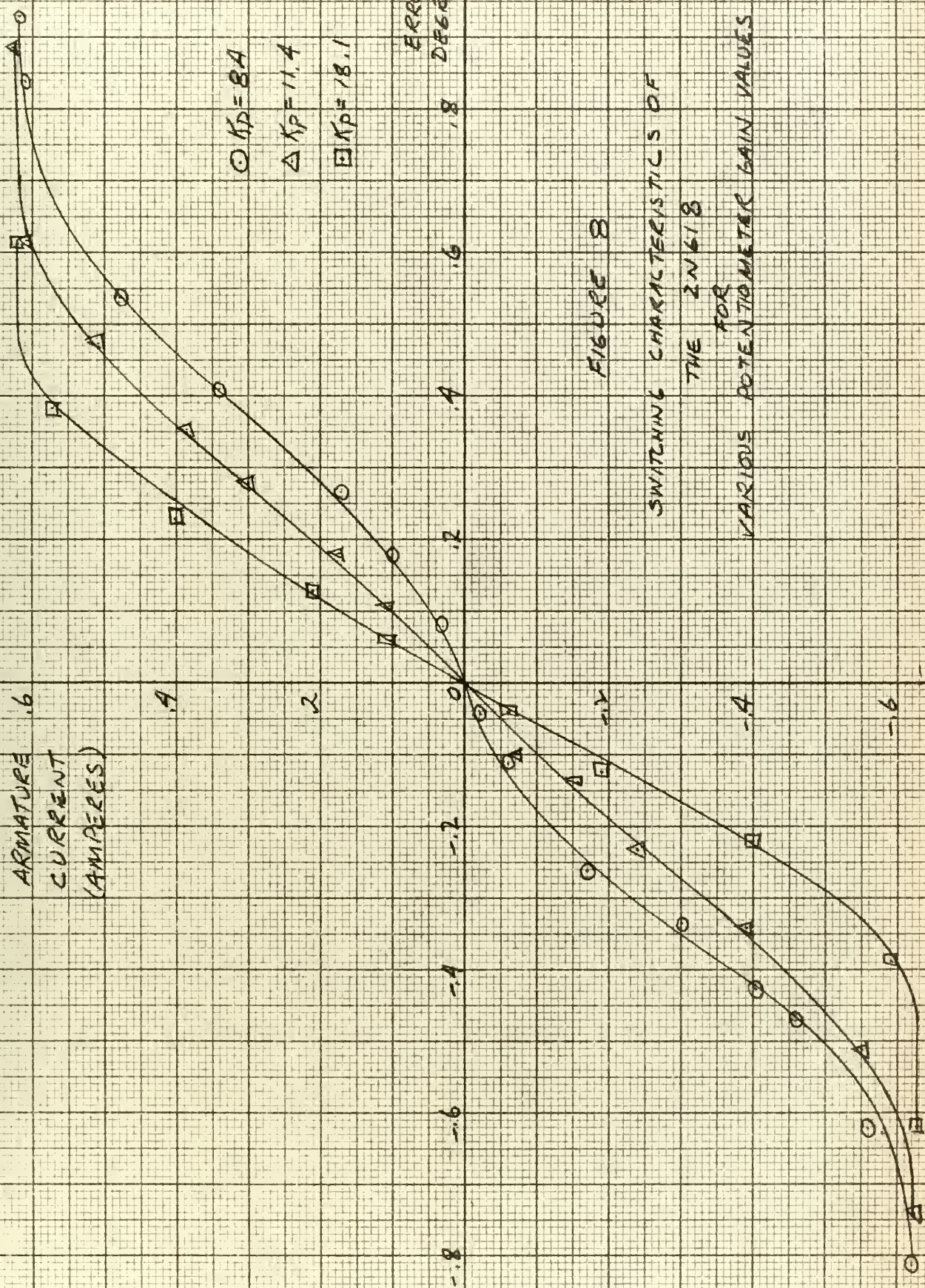


FIGURE 8
 SWITCHING CHARACTERISTICS OF
 THE 2N618
 FOR
 VARIOUS POTENTIOMETER GAIN VALUES

therefore, in both cases, the current-error curves would transform directly into torque-error curves with only a change in vertical scale. No dead zone exists in the switching characteristic, and nearly perfect dual mode, i.e. linear and saturated, operation results.

For the series motor the situation is somewhat different. Again, assuming a linear flux-magnetizing force relationship, developed torque is proportional to the square of the motor current. The effect of squaring the current-error curves of Fig. 8 for the 2N618 is shown in Fig. 9. With transistor switching the torque-error curves for the series motor is not linear but is of course more nearly a second degree parabola. There is no zone of zero torque as in the contactor type relay, but dependent on K_a , K_p and h_{fe} there exists a zone of very small or negligible torque near the zero error position. Were it not for coulomb friction a system switched even with this characteristic would have no position error. Since the above is just wishful thinking some definition of dead zone is required here. Definitions suggested are

- 1) the error required to develop breakaway torque, the motor being initially at rest
- 2) the error existing at some specific percentage of maximum torque
- 3) the error defined by the intersection of a line tangent to the straight portion of the torque curve with the error axis.

These definitions are depicted in Fig. 10.

Since the switching circuit is symmetrical, assuming symmetrical amplifier operation, the switching curves will always be symmetrical. In addition, no hysteresis loop is present as in the case of the magnetic relay. Even though the transistor is operated in the saturated region the time for the device to recover from saturation is orders of magnitude shorter than

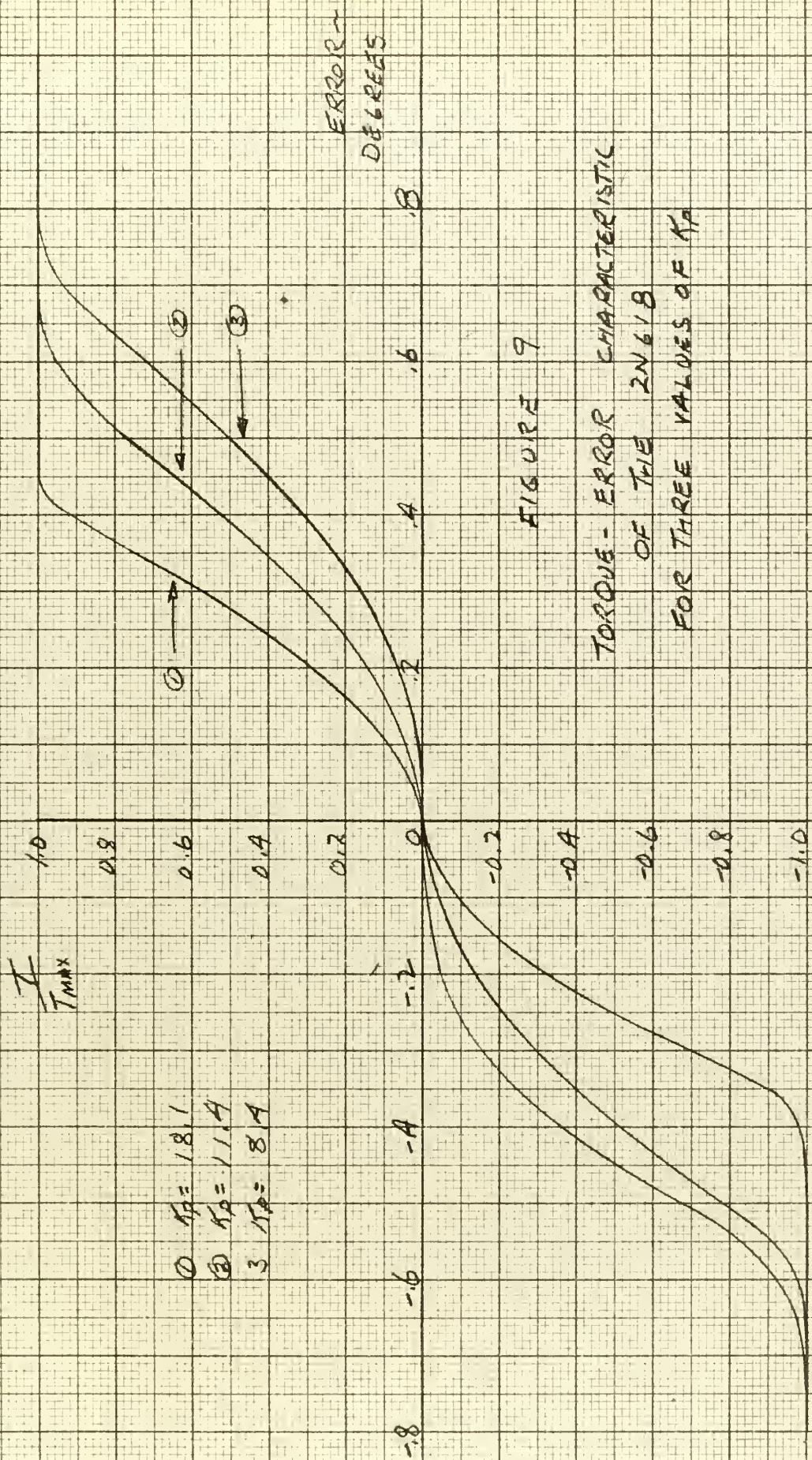
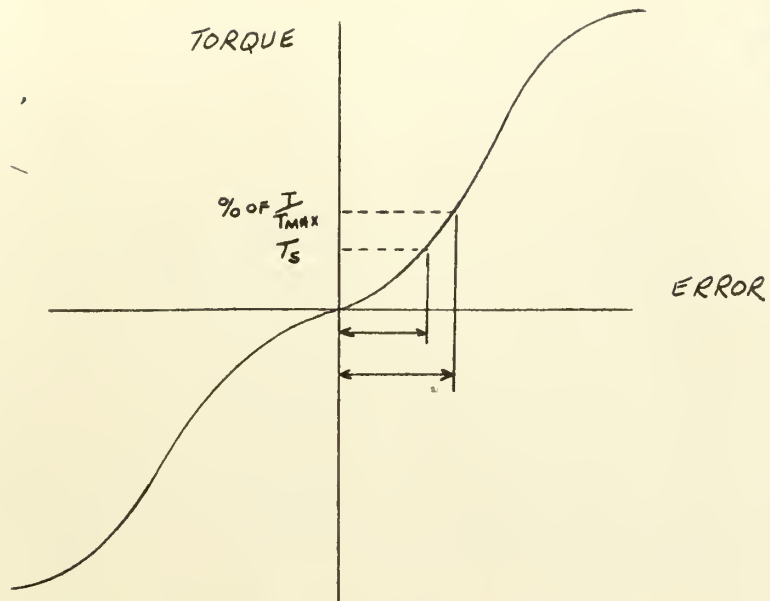
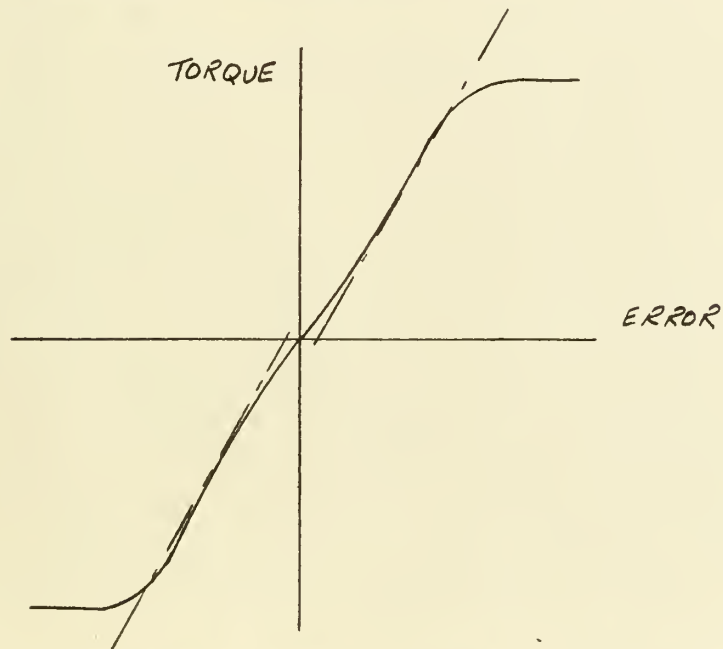


FIGURE 9
TORQUE - ERROR CHARACTERISTIC
OF THE 2N618
FOR THREE VALUES OF K_p



a) Dead Zone Defined By Percent Of Maximum Torque Or By Breakaway Torque



b) Dead Zone Defined By Intersection Method

Figure 10

Methods Of Defining Dead Zone

the relatively slow switching rates required to follow the error signal. Thus regardless of whether the error is increasing or decreasing the same switching characteristic applies. For these reasons the stipulation that the dead zone is plus or minus so many degrees from the zero error position can also be made.

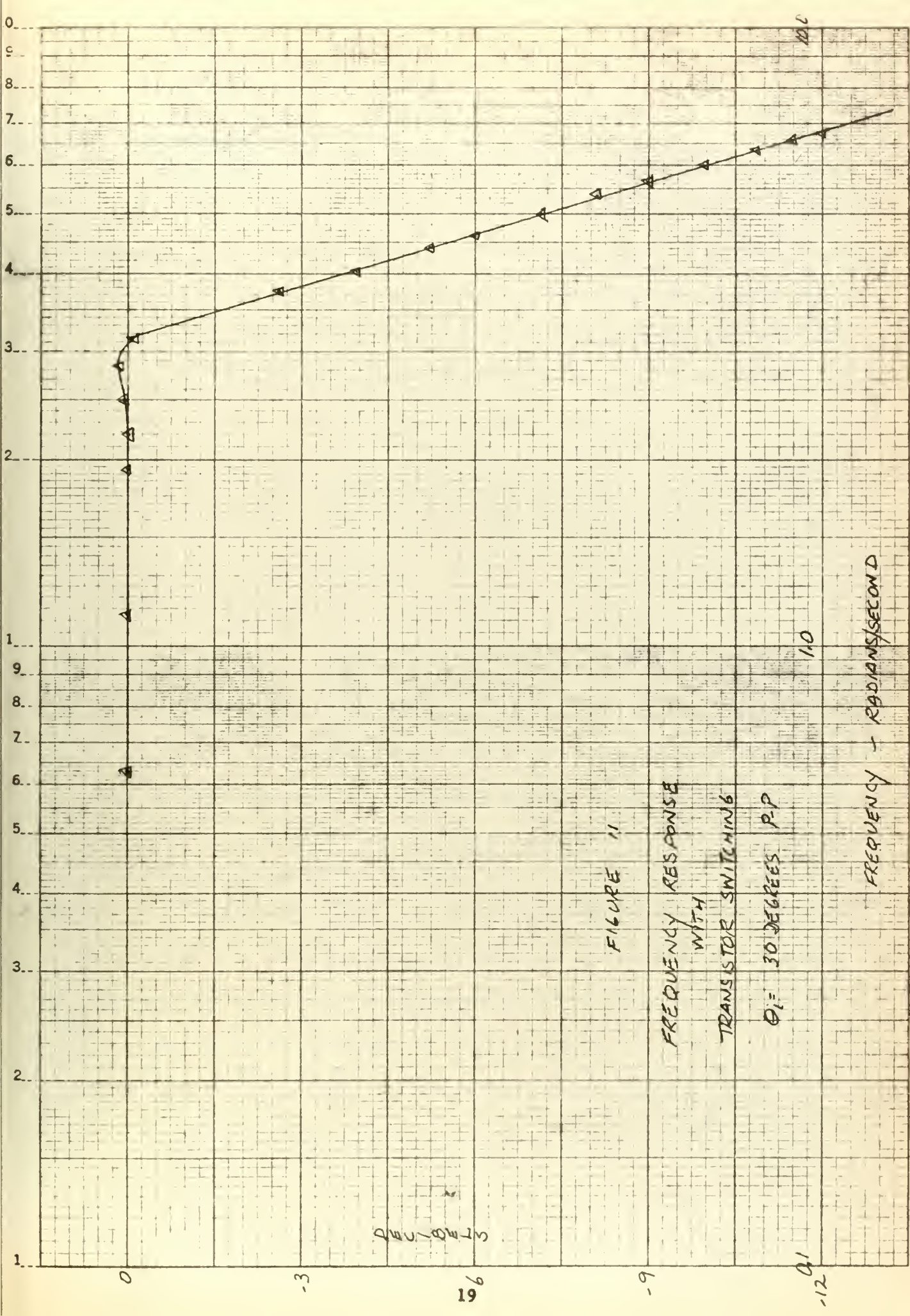
Using the last of the dead zone definitions given above, switching dead zones obtained with the 2N618 were as given in Table I.

TABLE I

Width of Dead Zone for Various Values of K_p	
K_p	Width (degrees)
8.4	0.45
11.1	0.39
14.5	0.29
18.1	0.21
27.8	0.13

6. Frequency Response of the System.

Discontinuous systems of the relay servo type frequently prove to have transfer functions of the $\frac{1}{s^2}$ type. The reasons for this are not fully understood. No detailed analysis of the frequency response of the experimental system was made to determine what effect, if any, transistor switching would have on system performance. One frequency response measurement was made to indicate that the system was of the $\frac{1}{s^2}$ type. The response spectrum shown in Fig. 11 is for a sinusoidal input of thirty degrees peak to peak amplitude. The response is flat to an angular frequency of 3.14 radians per second after which it falls off at 12 db per octave.



7. Transient Response of the System.

a) Discussion of Switching Boundaries.

The more interesting aspects of operation resulting from dual mode control was thoroughly investigated. As shown by optimum relay servo response theory¹ the optimum switching curve is a curve of the general shape of Fig. 12. For an ideal relay the actual switching boundary is a single curve on the phase plane. For a relay with dead zone and hysteresis the switching boundary is the familiar family of four lines representing positive and negative relay pull-in and drop-out points.

For the dual mode servo an intermediate zone of operation, dependent on system design and compensation, exists somewhere on the phase plane. To illustrate the region and bounds of this region which results from transistor switching consider the case of the constant armature current shunt motor. The torque-error characteristic is assumed to consist of a linear and torque saturated region as shown in Fig. 13. This relationship for the shunt motor is not a bad approximation, as was shown previously the current-error and therefore torque-error curves very closely approximate the ideal. The shunt motor case is chosen so that the current-squared torque relationship of the series motor does not complicate the mathematics so much that the ideas to be expressed are obscured.

For the shunt motor with constant armature current

$$(2) \quad T = k_T \phi i_a = k_T k_\phi i_f i_a = K_T i_f$$

Equation (2) also assumes a linear magnetization characteristic.

For the second order system,

$$(3) \quad \frac{T \ddot{\theta}}{P} + \frac{f \dot{\theta}}{P} = T = K_T i_f$$

¹Lewis, J. B., Optimum Response Relay Servos, Control Engineering, July, 1960.

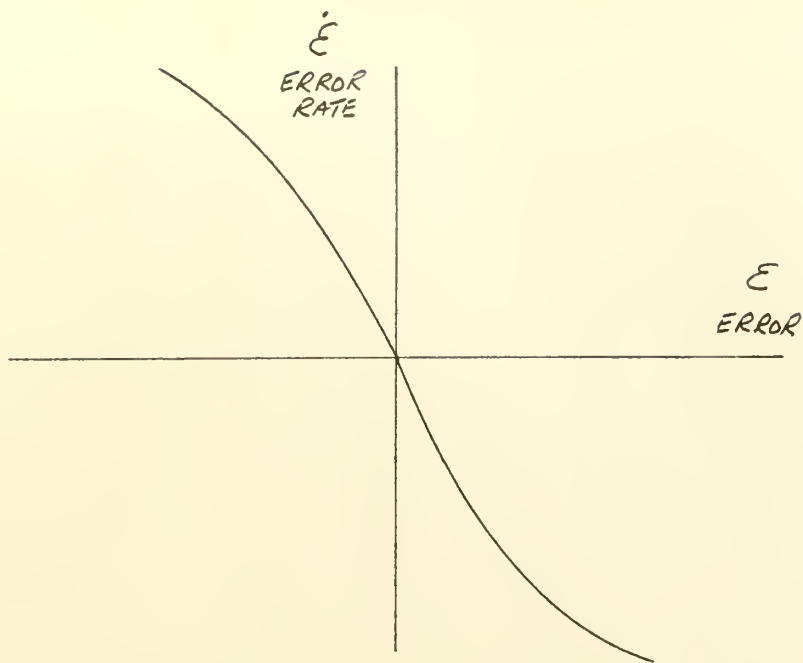


Figure 12. General Shape Of The Optimum Switching Curve For A Second Order System

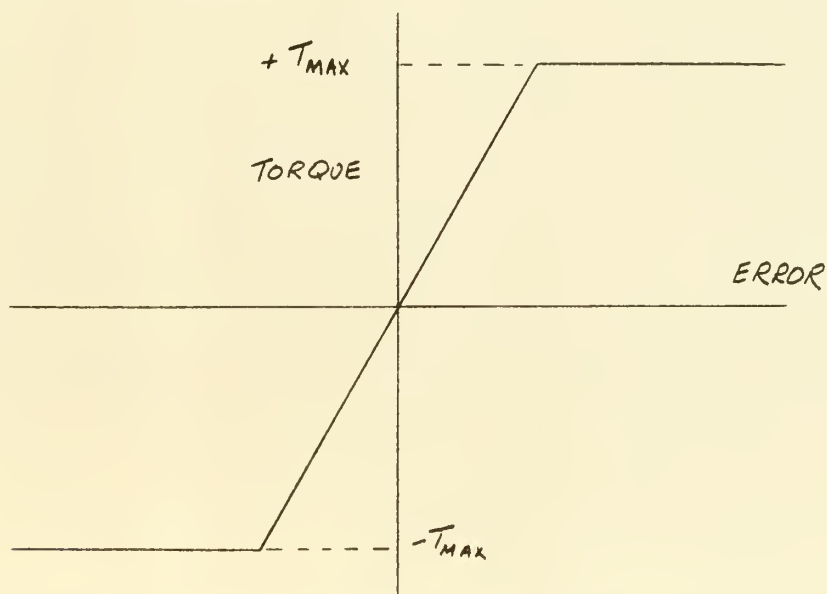


Figure 13. Torque-Error Characteristic For Idealized Dual Mode Operation

From the torque error characteristic, Fig. 13.

$$(4a) \quad J = J_{MAX} \frac{E}{E_{MAX}} \quad \text{for } -E_{MAX} \leq E \leq +E_{MAX}$$

and

$$(4b) \quad J = J_{MAX} \operatorname{sgn} E \quad \text{for } |E| \geq \pm E_{MAX}$$

In this example the error signal which activates the servo motor is the field current if so that

$$(5) \quad E = K_a K_p h_{FE} (\theta_i - \theta_o) - K_a h_{FE} h \dot{\theta}_o$$

thus

$$(6) \quad \frac{1}{\rho} \ddot{\theta}_o + \frac{f}{\rho} \dot{\theta}_o = K_T [K_a K_p h_{FE} (\theta_i - \theta_o) - K_a h_{FE} h \dot{\theta}_o] = K_T E$$

$$\text{for } -E_{MAX} \leq E \leq +E_{MAX}$$

$$\text{and } (7) \quad \frac{1}{\rho} \ddot{\theta}_o + \frac{f}{\rho} \dot{\theta}_o = J_{MAX} \operatorname{sgn} E \quad \text{for } |E| \geq \pm E_{MAX}$$

Equation (6) pertains to the linear zone and equation (7) to the saturated zone of operation.

The dividing lines in the phase plane can be determined from these equations. From equation (6) the line for zero torque is defined when the error signal is zero. Considering a step input where

$$\theta_i(t) = A u(t) \quad \text{for } t \geq 0$$

$$\text{then } (8) \quad K_T [K_a K_p h_{FE} (A - \theta_o) - K_a h_{FE} h \dot{\theta}_o] = 0$$

from which the equation of the zero torque dividing line is

$$(9) \quad \dot{\theta}_o = -\frac{K_p}{h} \theta_o + \frac{K_p}{h} A$$

This is the same equation as that for an ideal relay. The slope of the dividing line is $-\frac{K_p}{h}$ and the θ_o axis intercept is at A. See Fig. 14.

The torque saturated region exists when the error signal is equal to or greater than that necessary to produce maximum torque. The dividing line occurs when

$$E = \pm E_{MAX}$$

From equation (7), with $E = \pm E_{MAX}$

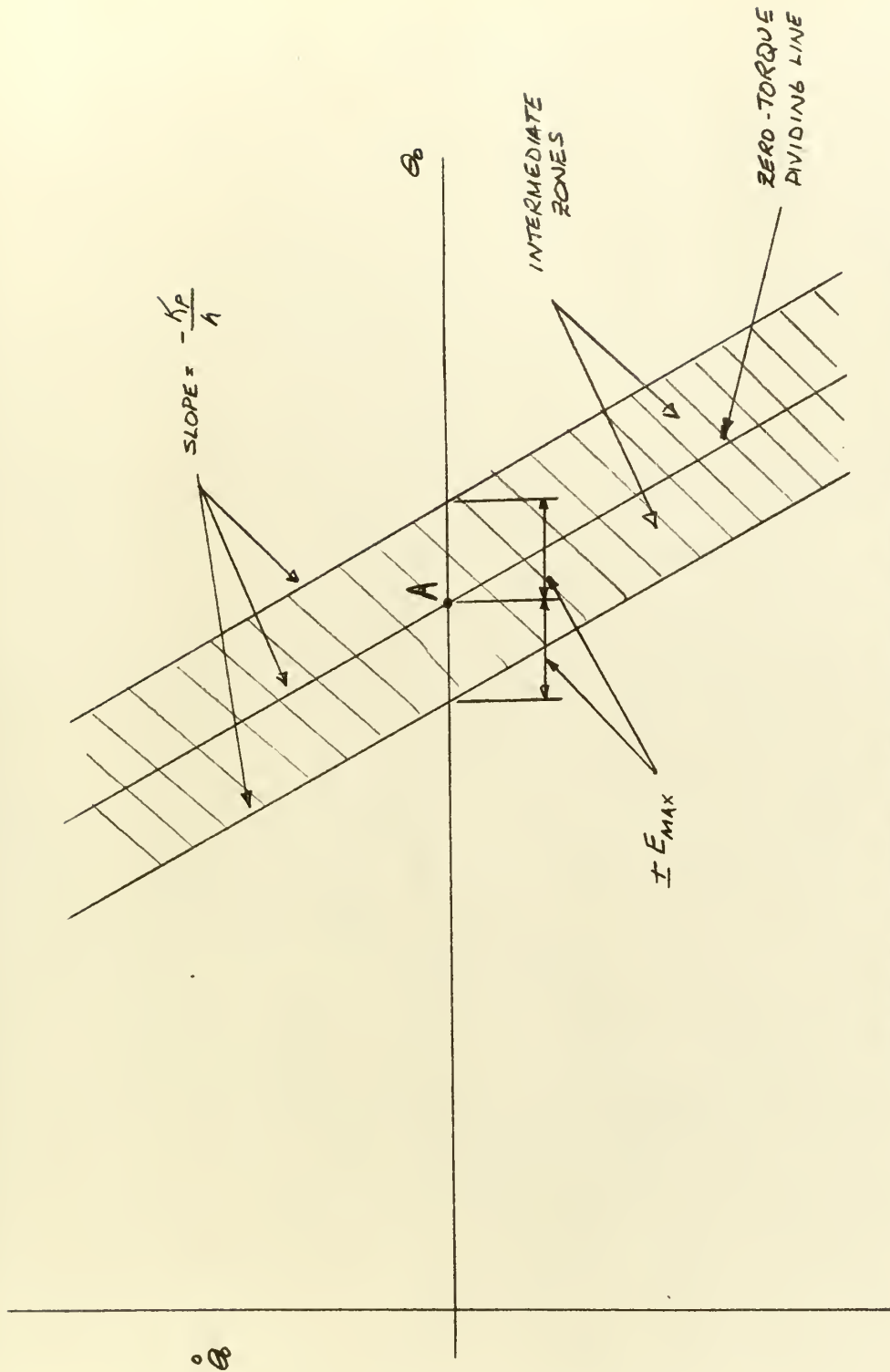


Figure 14. Phase Plane Dividing Lines of A Second Order System With Dual Mode Operation

$$(10) \quad K_a K_p h_{FE} (A - \Theta_0) - K_a h_{FE} h \dot{\Theta}_0 = \pm E_{max}$$

from which

$$(11) \quad \dot{\Theta}_0 = - \frac{K_p}{h} \Theta_0 + \frac{K_p}{h} \left[A \mp \frac{E_{max}}{K_p K_a h_{FE}} \right]$$

This equation defines the boundary between the intermediate (in this case linear) zone of operation and the torque saturated region. The slope of the dividing lines is again $-\frac{K_p}{h}$ and the lines are therefore parallel to the zero torque dividing line. See Fig. 14. The intercepts on the Θ_0 axis are at

$$(12) \quad \Theta_0 = A \mp \frac{E_{max}}{K_p K_a h_{FE}}$$

Equation (12) shows what the experiments have indicated, namely that the width of the linear zone is a function of the two system constants, K_p and K_a , and of the forward current gain, h_{fe} , of the transistor.

Though this development has been for the shunt motor it is evident that the dividing lines for the series motor would be similarly situated on the phase plane. The intermediate region would not of course be linear but it would lie along and symmetrically to either side of the zero torque line as for the shunt motor case.

b) Discussion of Transient Response Tapes.

Varied but not entirely comprehensive curves of response to step inputs with the series motor were obtained to depict system operation. Four groups of tests were made. The first two groups were made with the tachometer generator connected to the gear train; the first group without tachometer feedback and the second with the feedback adjusted for optimum response. With the tachometer connected, due to brush and bearing friction of both motor and generator, the damping of the system was large. The latter two groups were run with the tachometer generator disconnected; the first group with no compensation and the second with lead

network compensation. These groups illustrate system operation with small damping. No quantitative analysis of the damping coefficient was undertaken, but qualitatively, because of the very small friction in the gear train, removing the tachometer generator from the gear drive reduced system friction by about one-half. Differences in response are obvious from the recordings which follow.

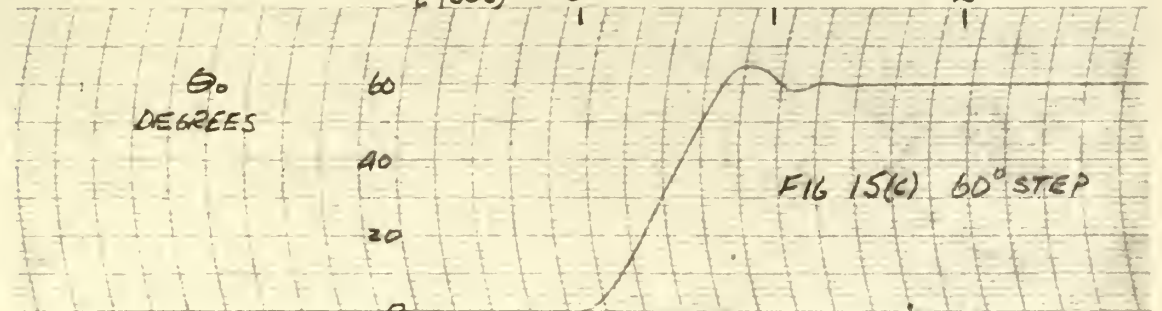
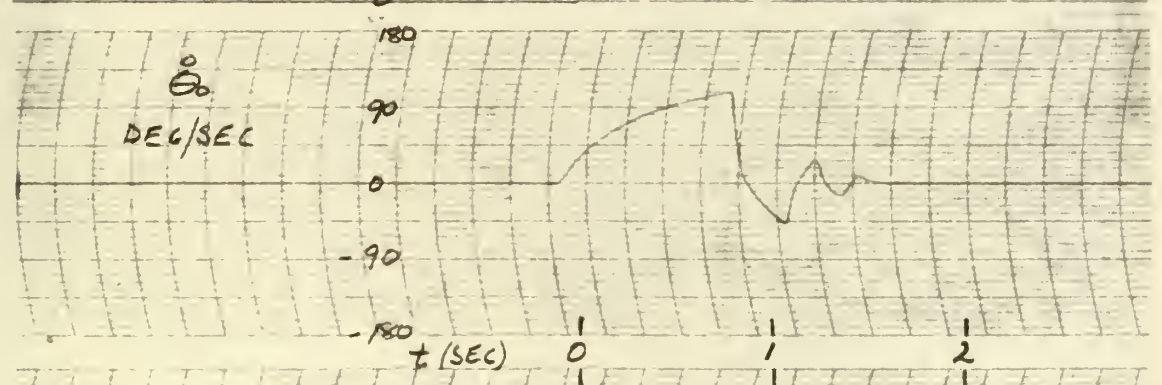
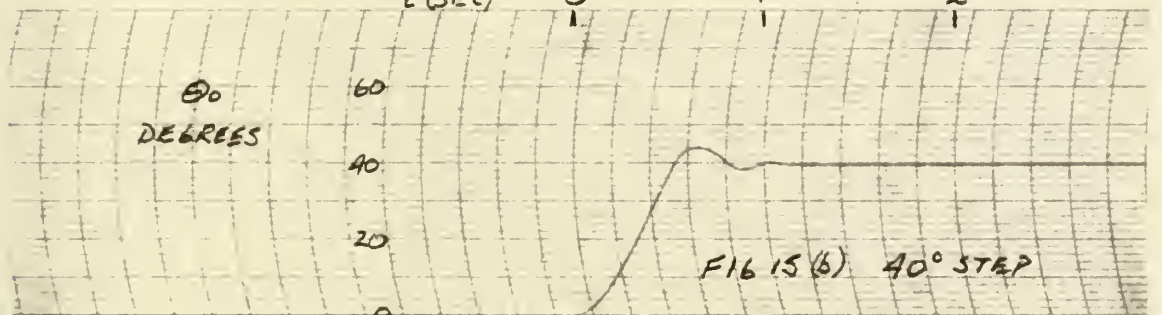
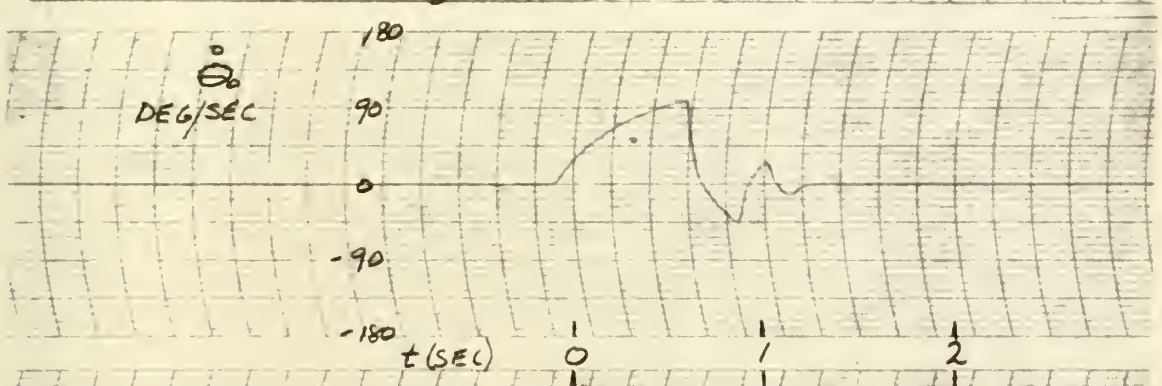
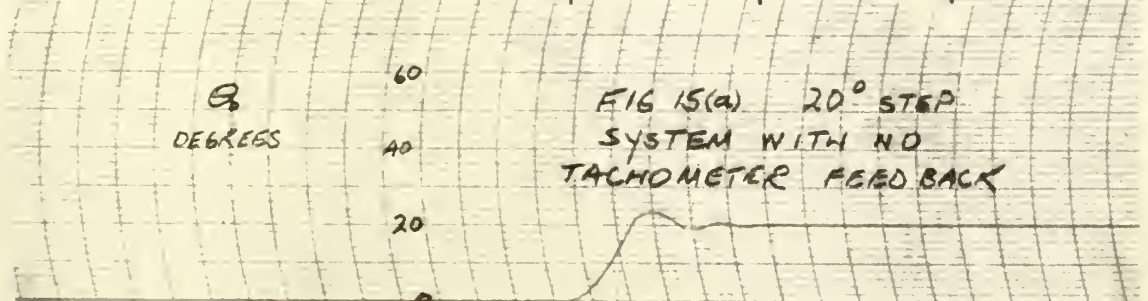
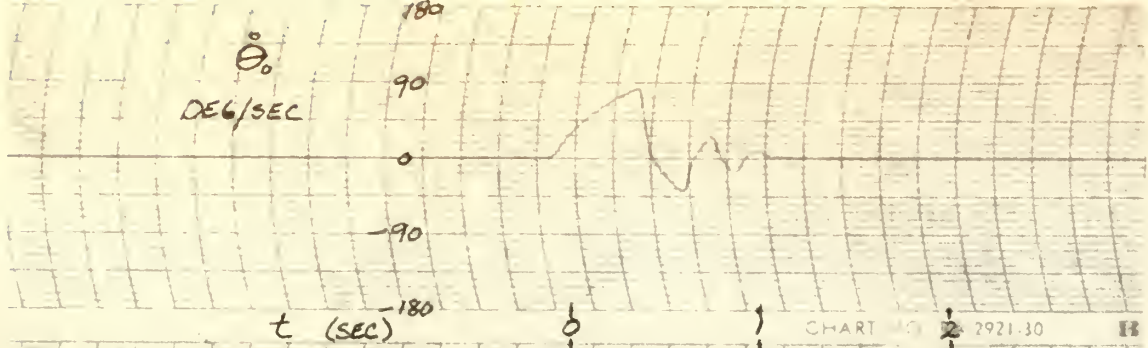
1) System with Tachometer Connected but no Tachometer Feedback.

Responses to step inputs of 20, 40 and 60 degrees were recorded. The error gain constant K_p was set for 14.5 volts/degree corresponding to curve b of Fig. 8. Traces of output velocity and position are shown in Fig. 15(a), (b) and (c). Response is similar to that of an underdamped linear system. The output position has a maximum overshoot after which the system oscillates toward and settles at the final output position. From the optimum relay servo standpoint one could consider these runs (without tachometer feedback) as being the case of worst possible case of switching error, where the actual switching boundary, the vertical axis, lies farthest from the optimum switching curve. Phase plane diagrams of these runs are shown in Fig. 16.

With the system in this configuration it was not possible to force the system into limit cycle operation regardless of the magnitude of the error gain constant or size of the step input. The value of K_p was set at the maximum obtainable, 27.8 volts/degree, practically double that of the previous runs. Maximum overshoot increased as would be expected, but the oscillations were highly damped and rapidly died out.

2) System with Tachometer Connected and Feedback Adjusted for Optimum Response to a 100 Degree Step

The value of K_p was set for 14.5 volts/degree. Responses to step



\dot{e}
DEG/SEC

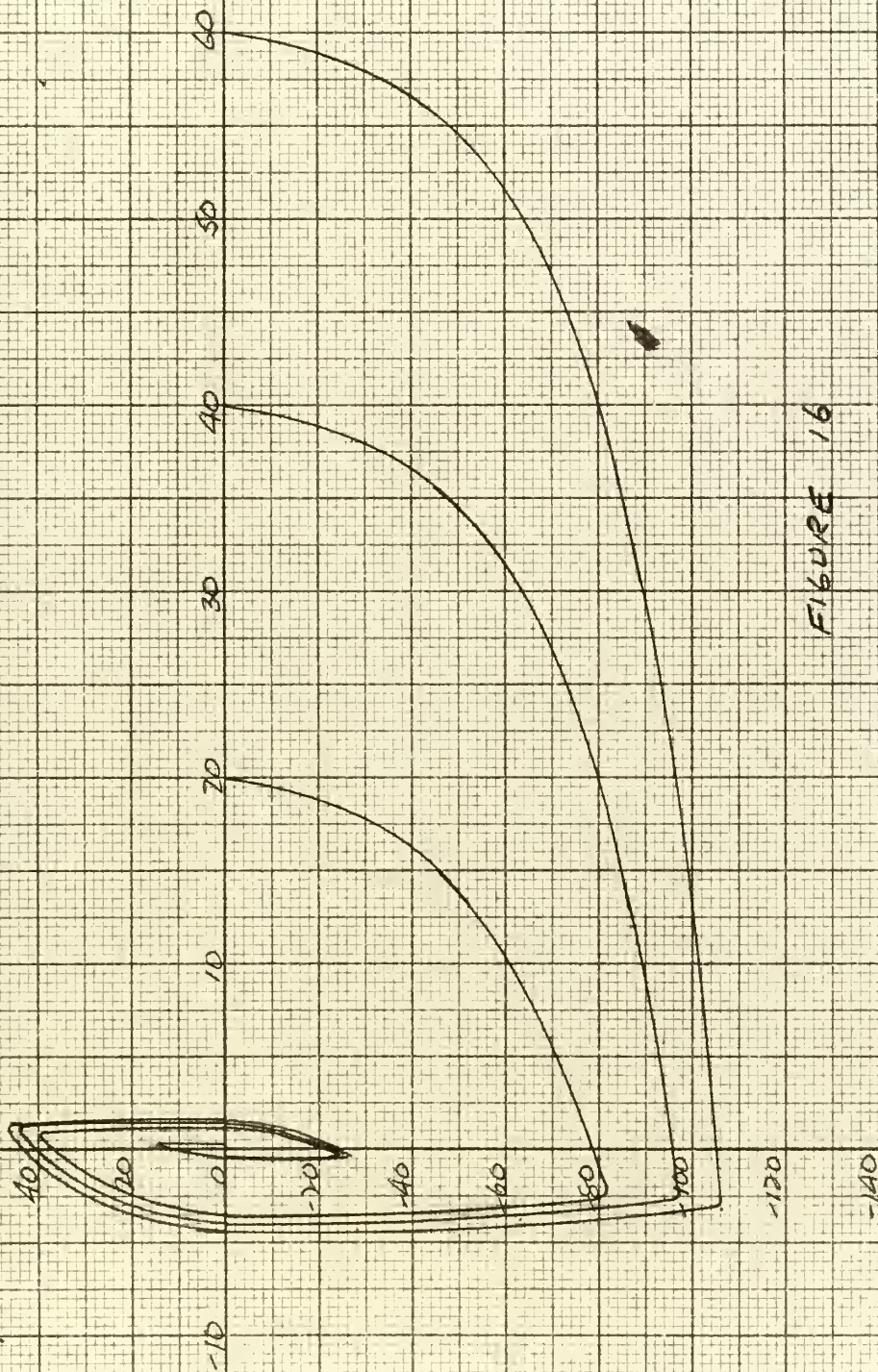


FIGURE 16

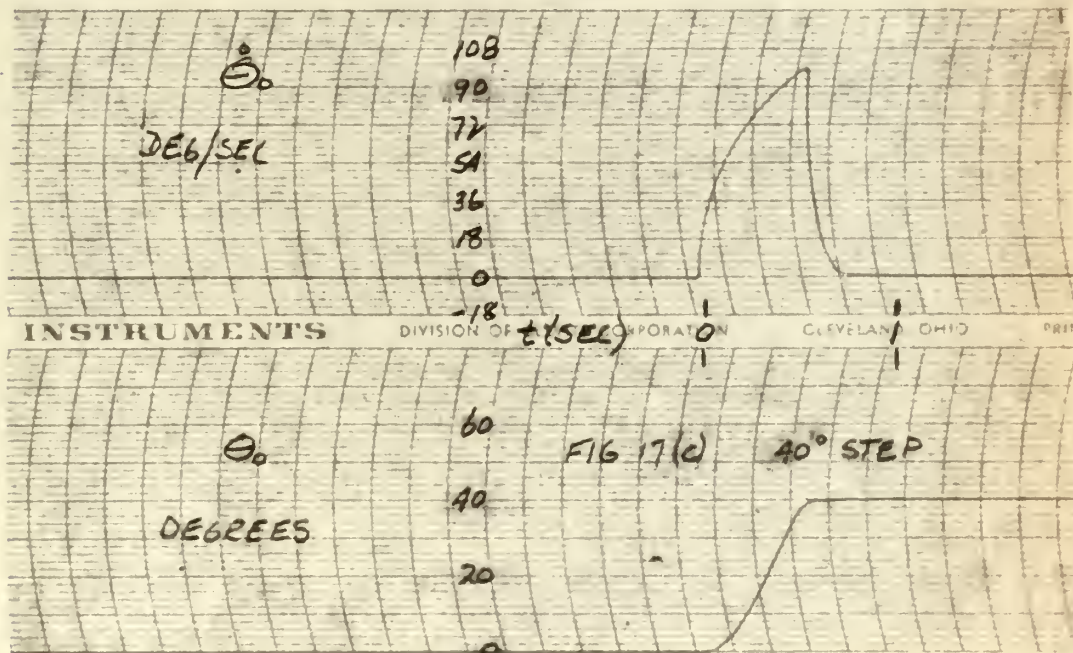
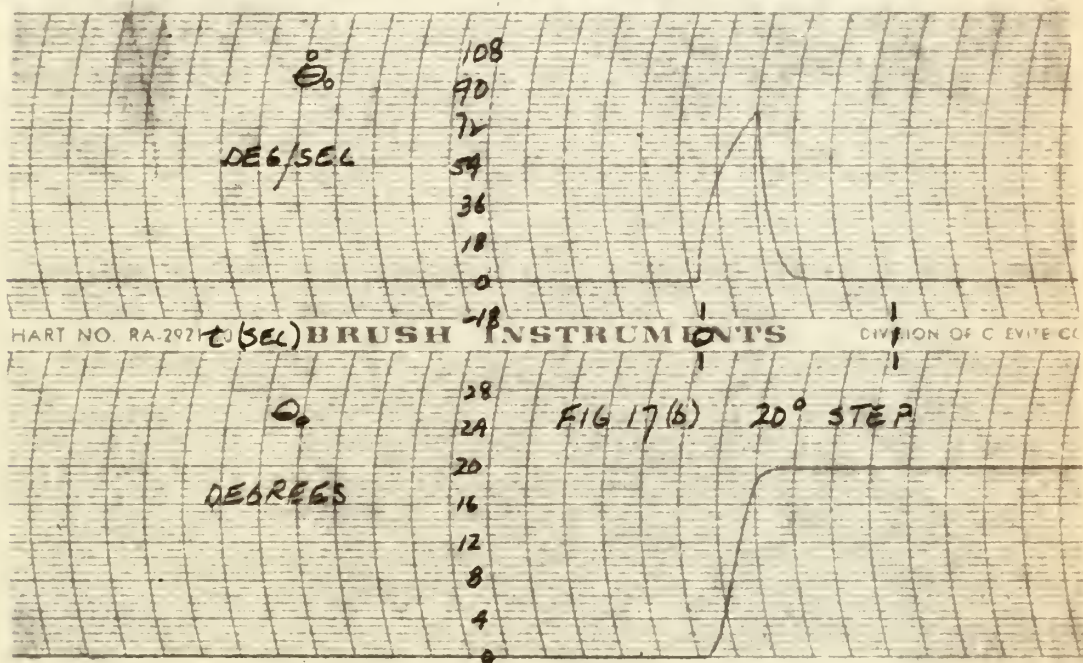
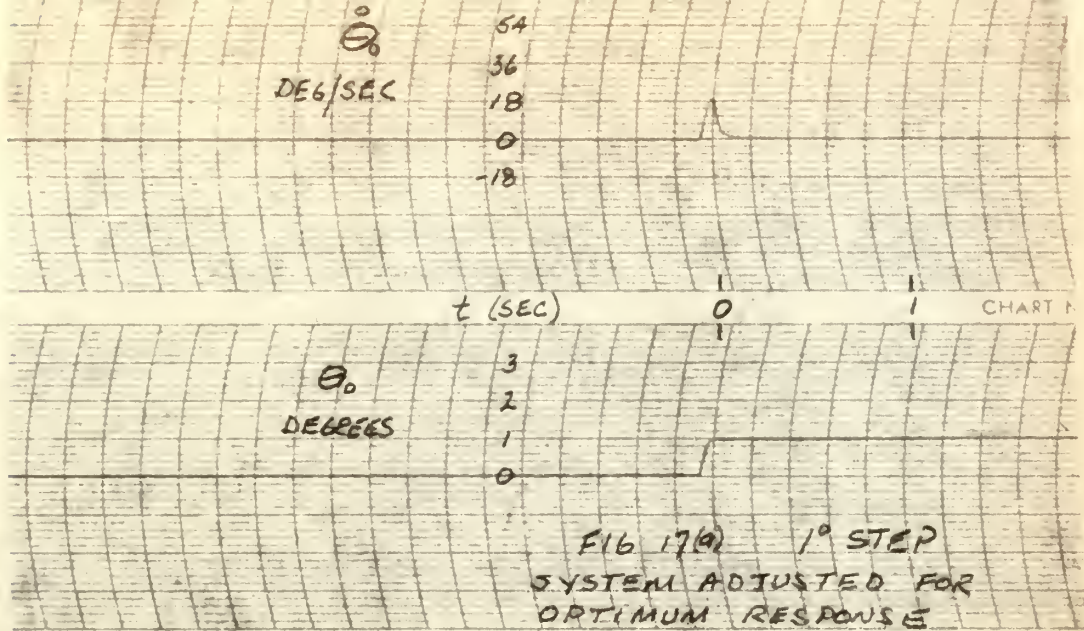
PHASE TRAJECTORIES OF SYSTEM
WITH
NO TACHOMETER FEEDBACK

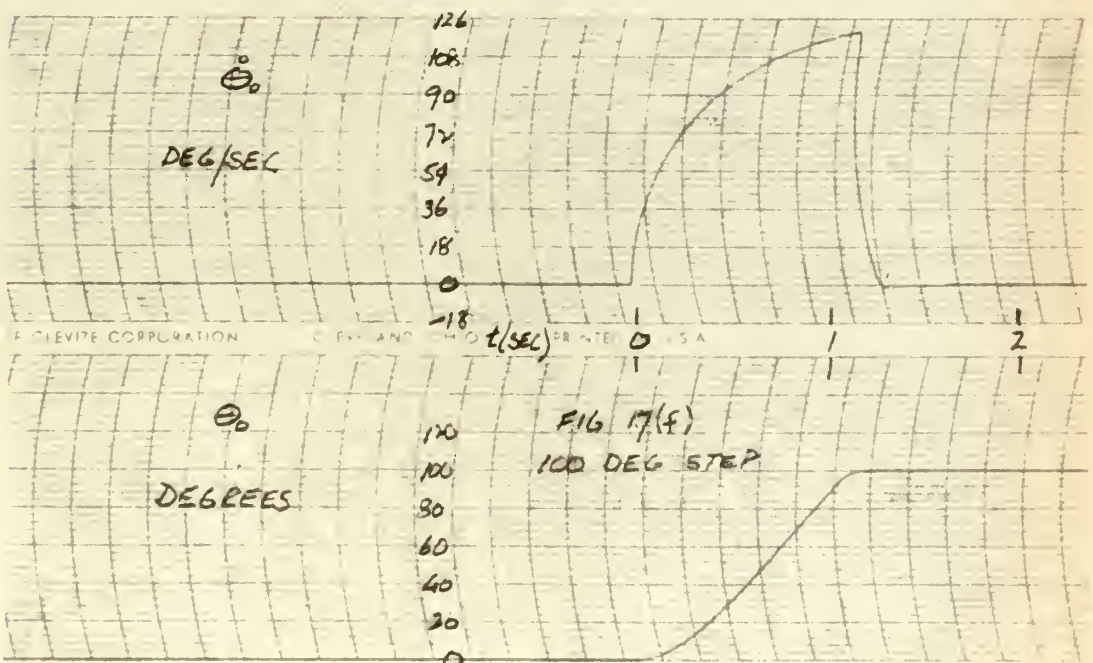
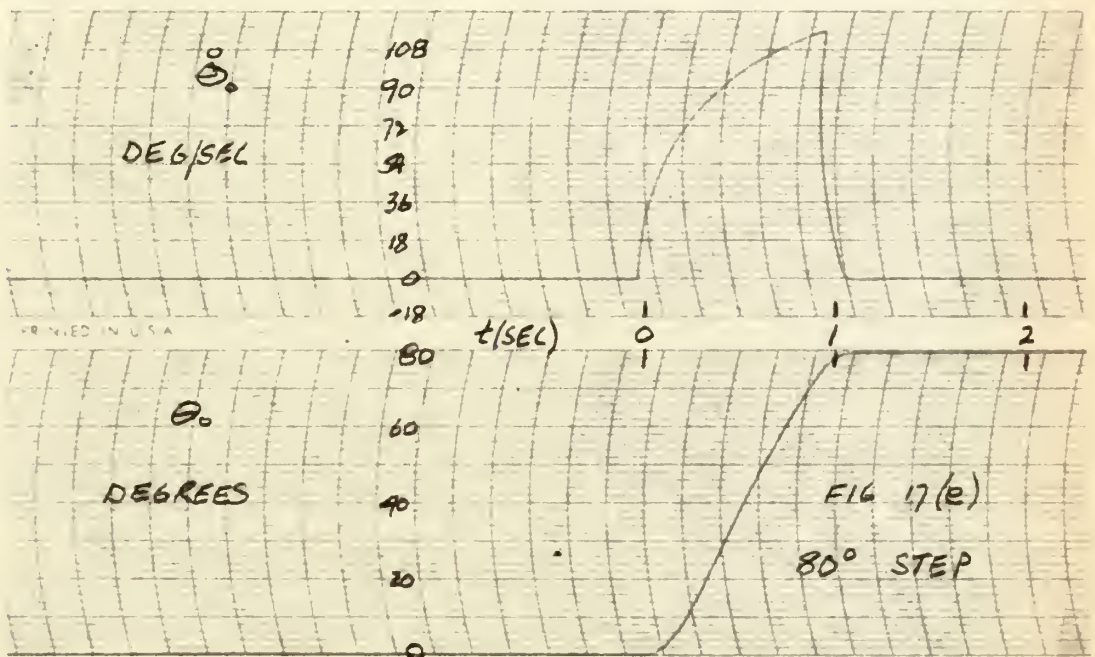
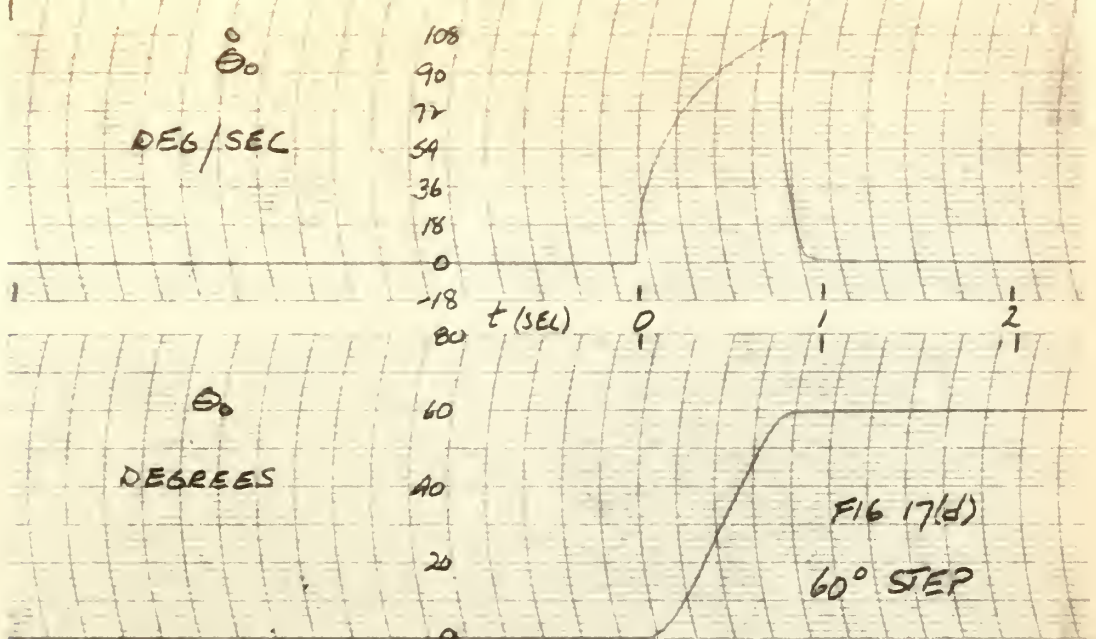
(FROM FIG 15)

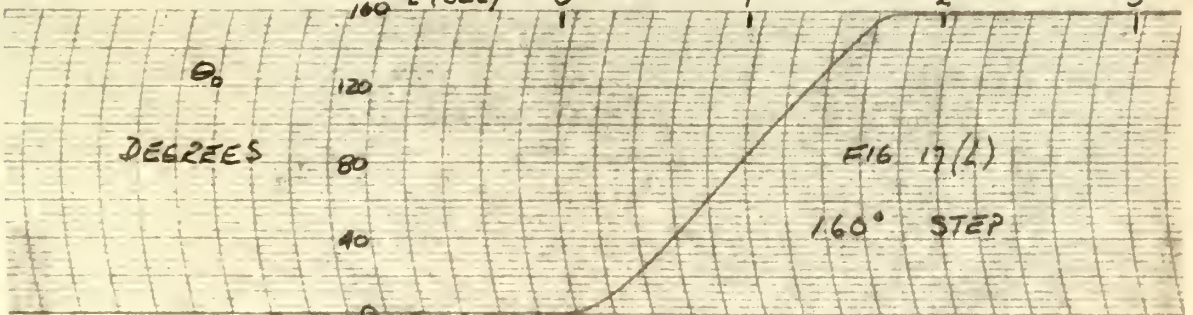
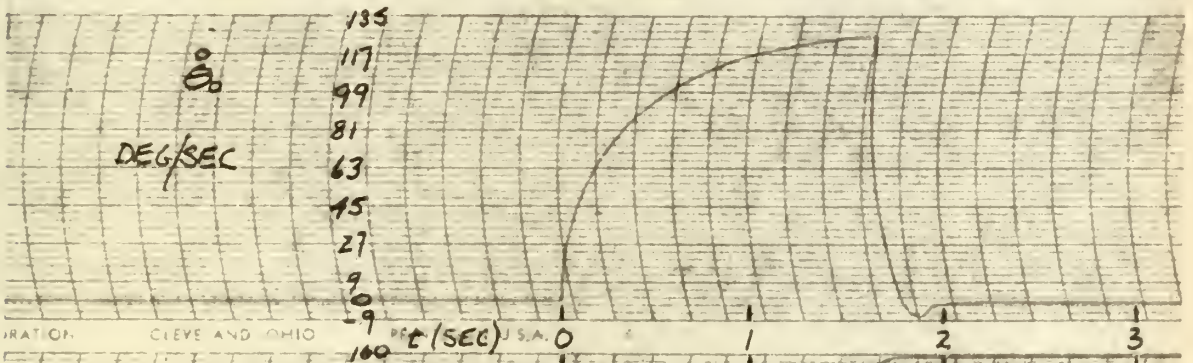
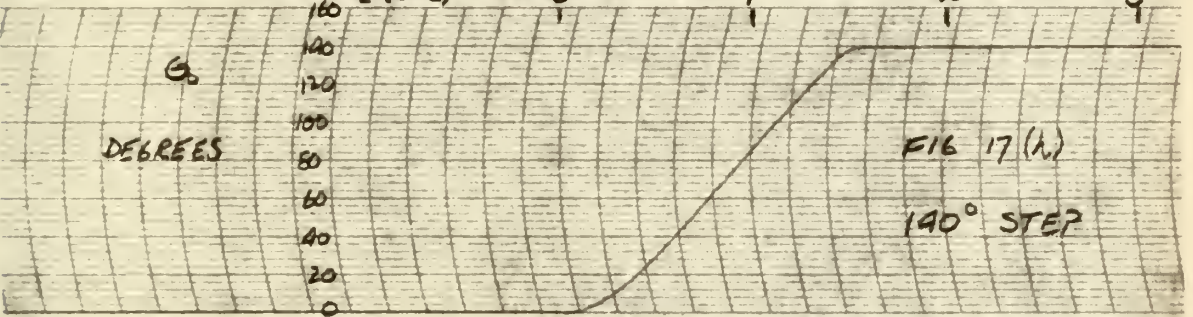
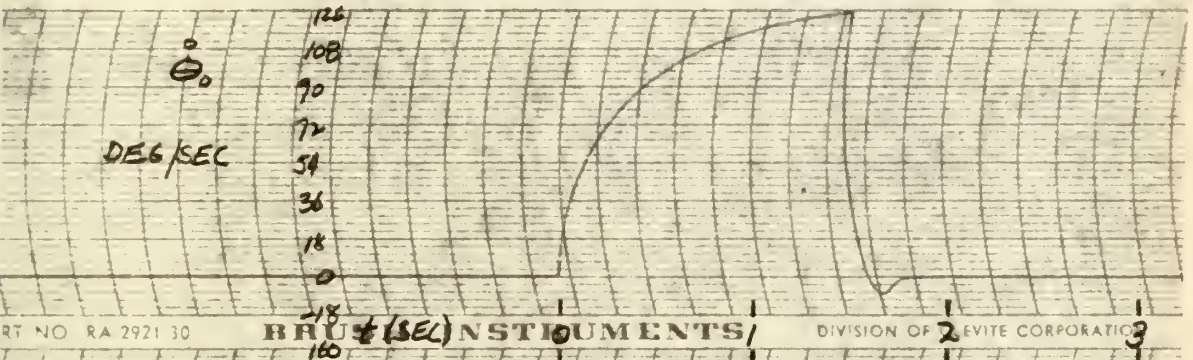
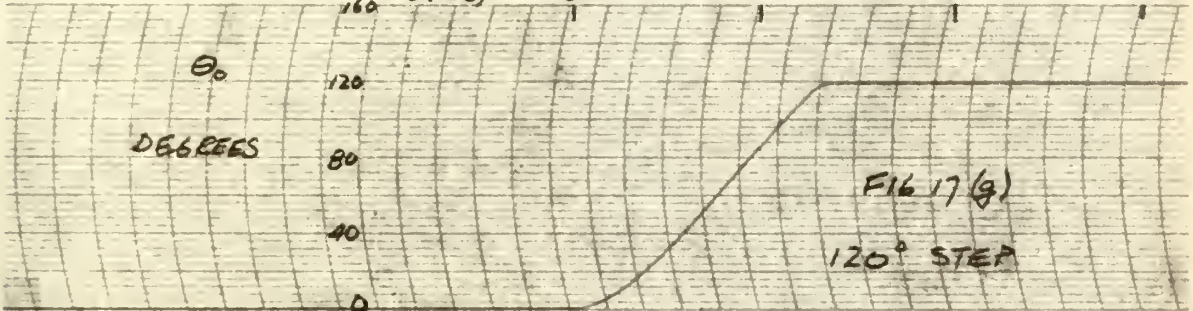
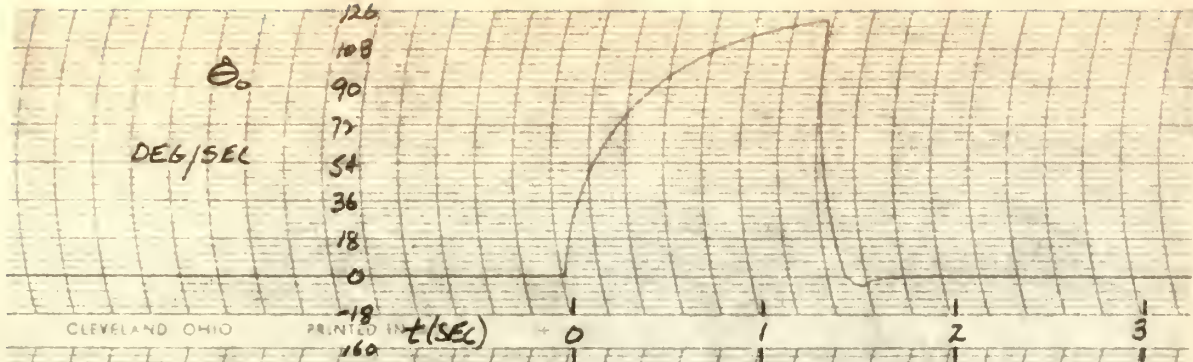
inputs ranging from one through 320 degrees were recorded. Traces of output velocity and position are shown in Fig. 18(a) through (j). As pointed out by Stockebrand² were the deceleration trajectory a straight line and therefore independent of initial error, so too would the optimum switching boundary be a straight line. The deceleration trajectory of the DC series motor, though closely approximating this, is slightly curved as in the pattern of Fig. 12. Thus, theoretically, with a straight line switching boundary the system can be adjusted for optimum response to only one size step input. For the system tested and set for optimum response to a 100 degree step it would be expected that for inputs less than this value the motor would tend to step-in toward the final position and for inputs greater would tend to overshoot. Phase plane diagrams drawn from the transient response curves of Fig. 17 are shown in Fig. 18. The steep deceleration trajectory typical of the series motor relay servo is evident here. As the size of the step input increases the phase trajectory tends more toward overshooting the final position, yet from the phase plane as well as from the recording of output position it is difficult to determine if deadbeat response is not achieved. This trend from step-in to overshoot with increase in initial error is, however, discernable from the recording of output velocity where, at the end of the deceleration curve, the trace either breaks sharply and slowly approaches zero velocity or overshoots and returns indicating a reversal of motor direction.

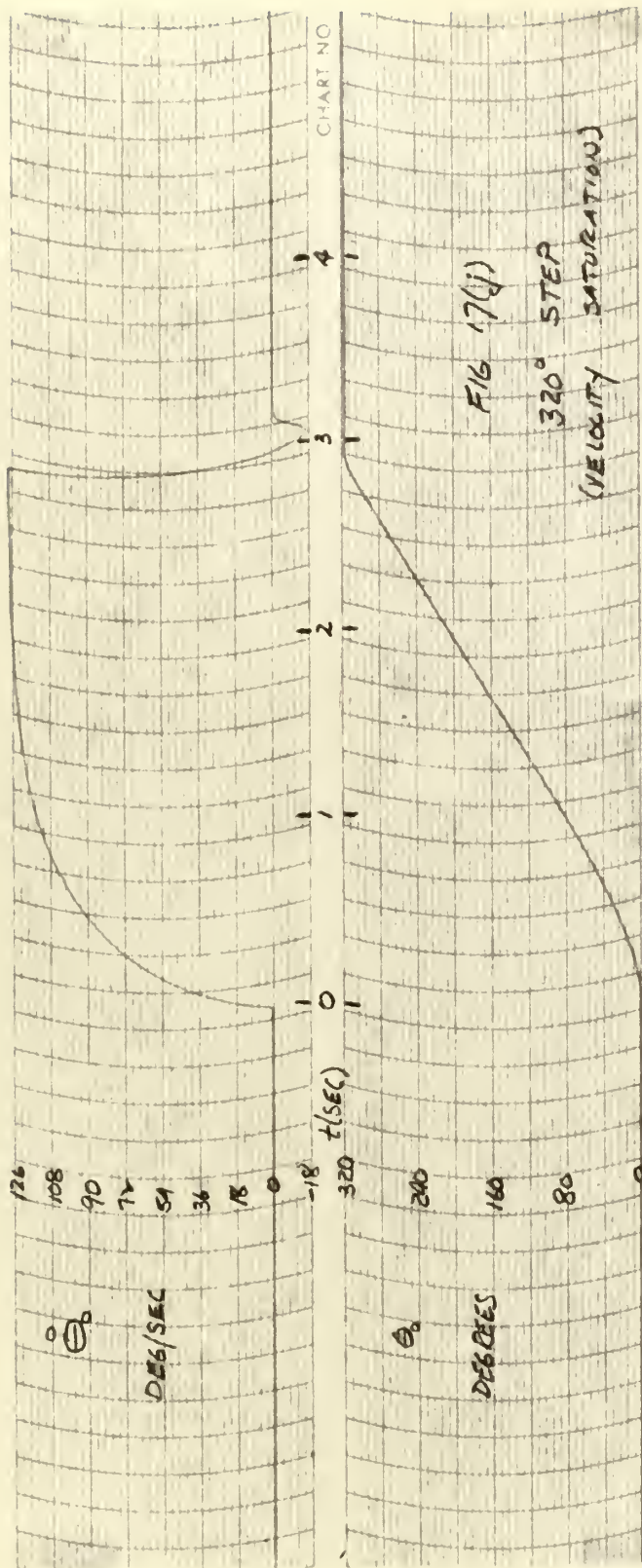
As in the first group of runs the potentiometer gain was set at the maximum value in an attempt to force the system into limit cycle operation.

²Stockebrand, A. P., Experimental Study of Relay Servo Optimization Using a Series Motor, Thesis, USNPS, 1959.









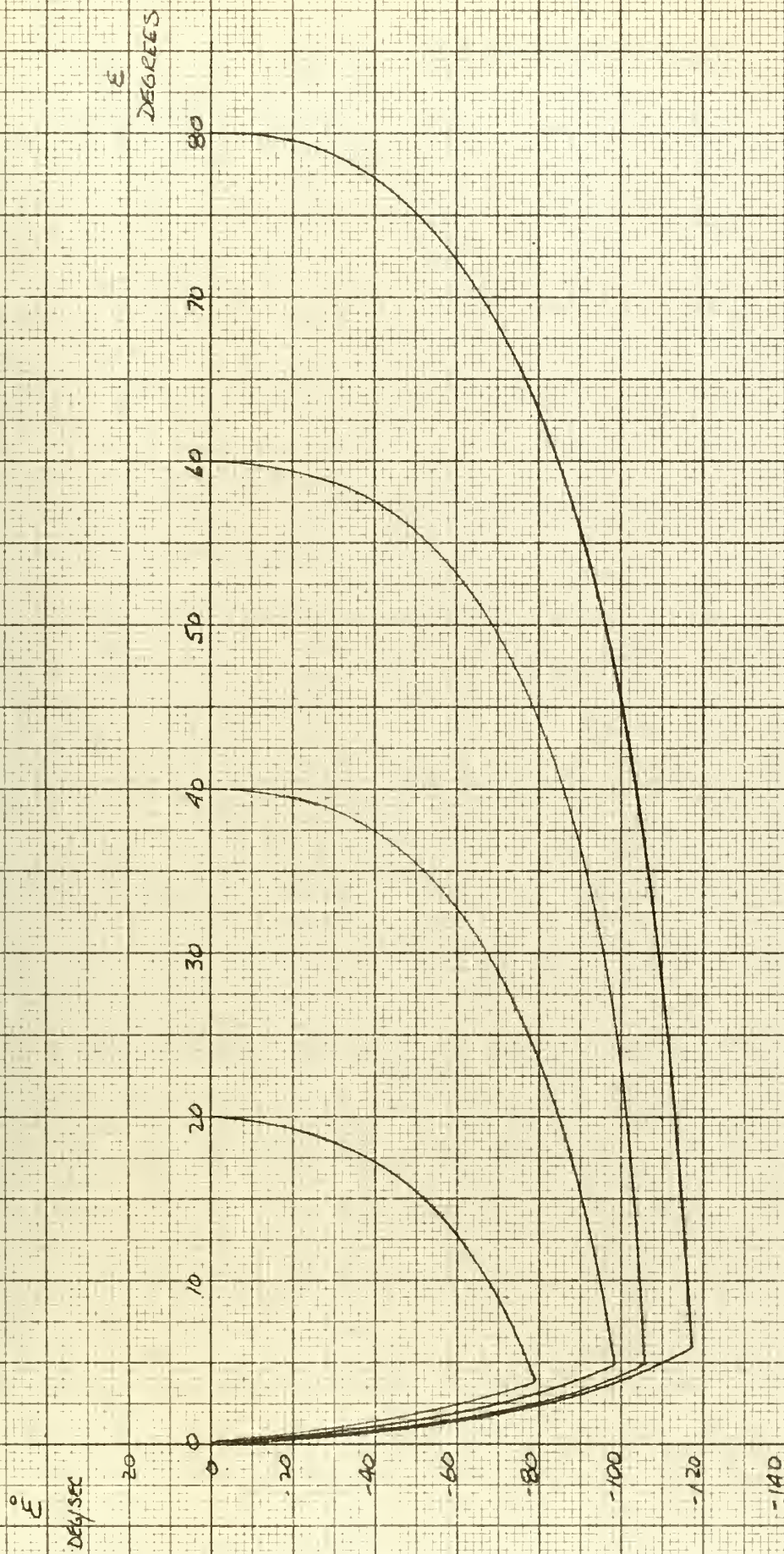


FIGURE 18

PHASE TRAJECTORIES OF SYSTEM WITH TACHOMETER
FEEDBACK ADJUSTED FOR OPTIMUM RESPONSE

Tachometer feedback was readjusted as necessary to obtain deadbeat response to a 100 degree step. Inputs were varied between one and 320 degrees (velocity saturation). As would be expected from the results of the first group of runs no limit cycles were obtained.

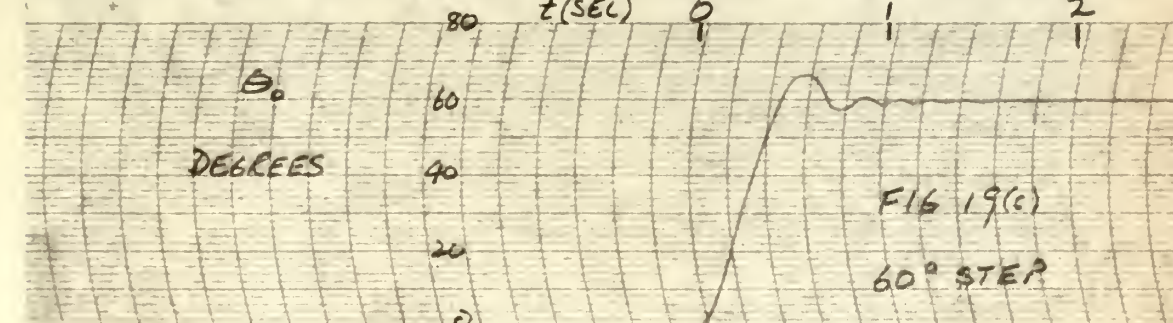
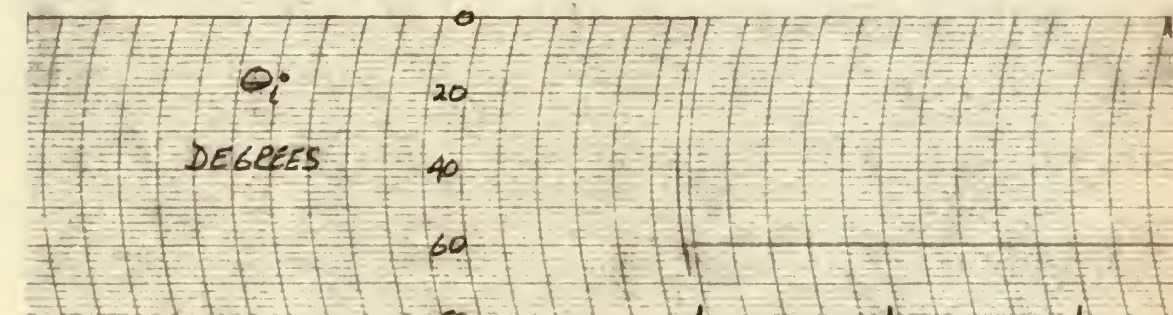
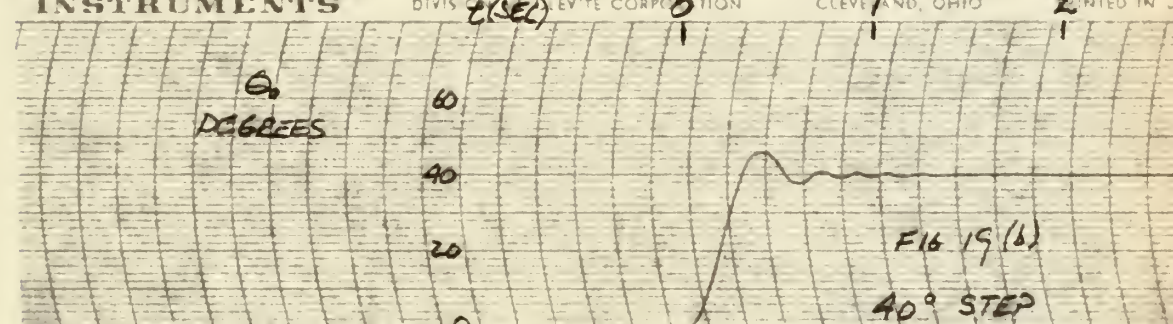
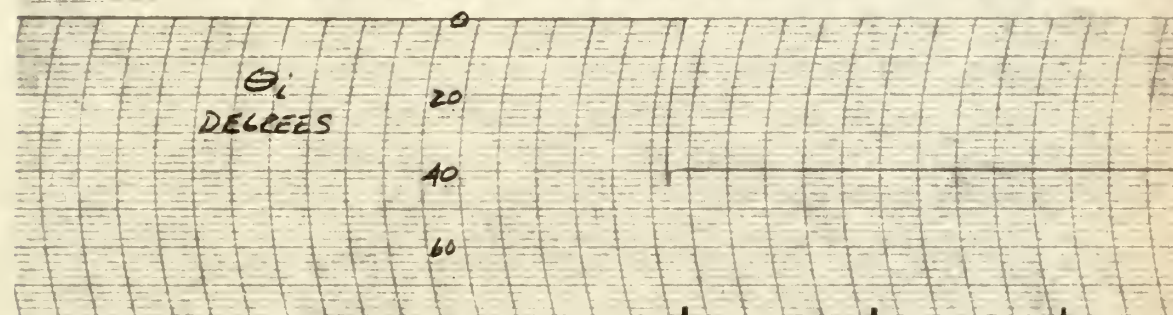
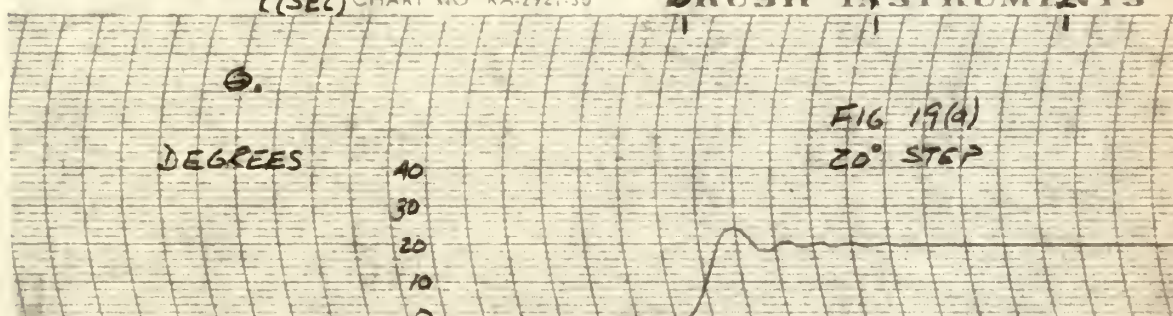
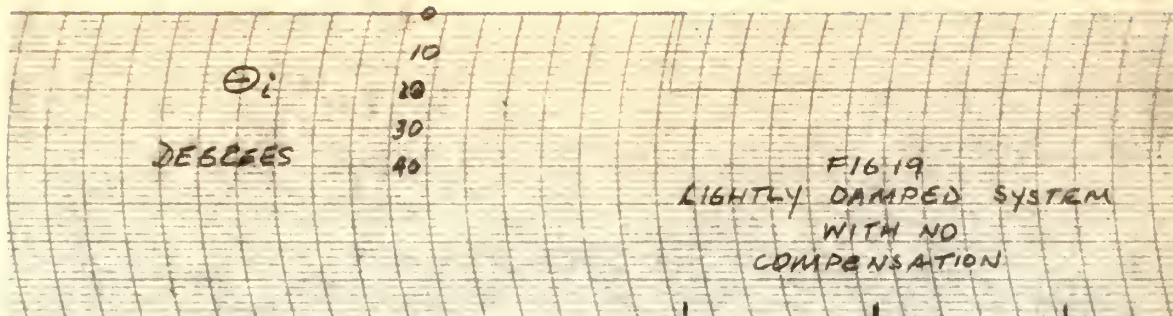
3) System Operation with Tachometer Disconnected and no Compensation.

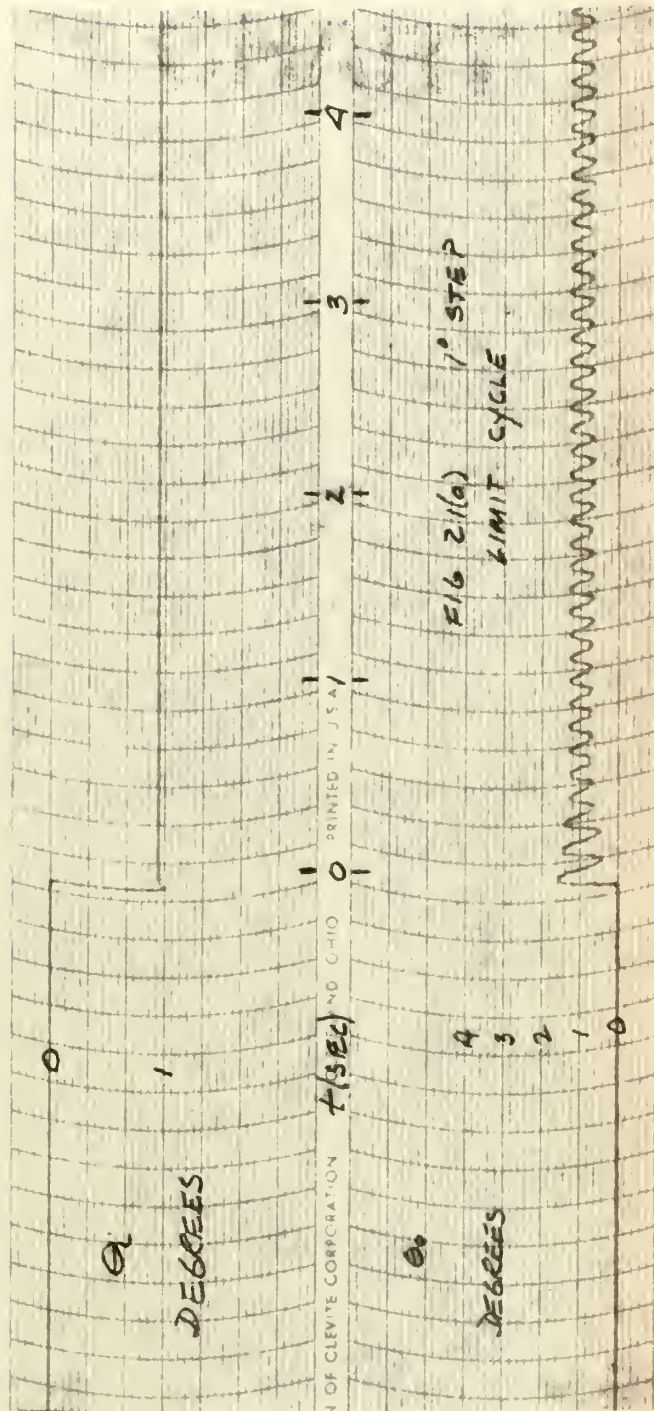
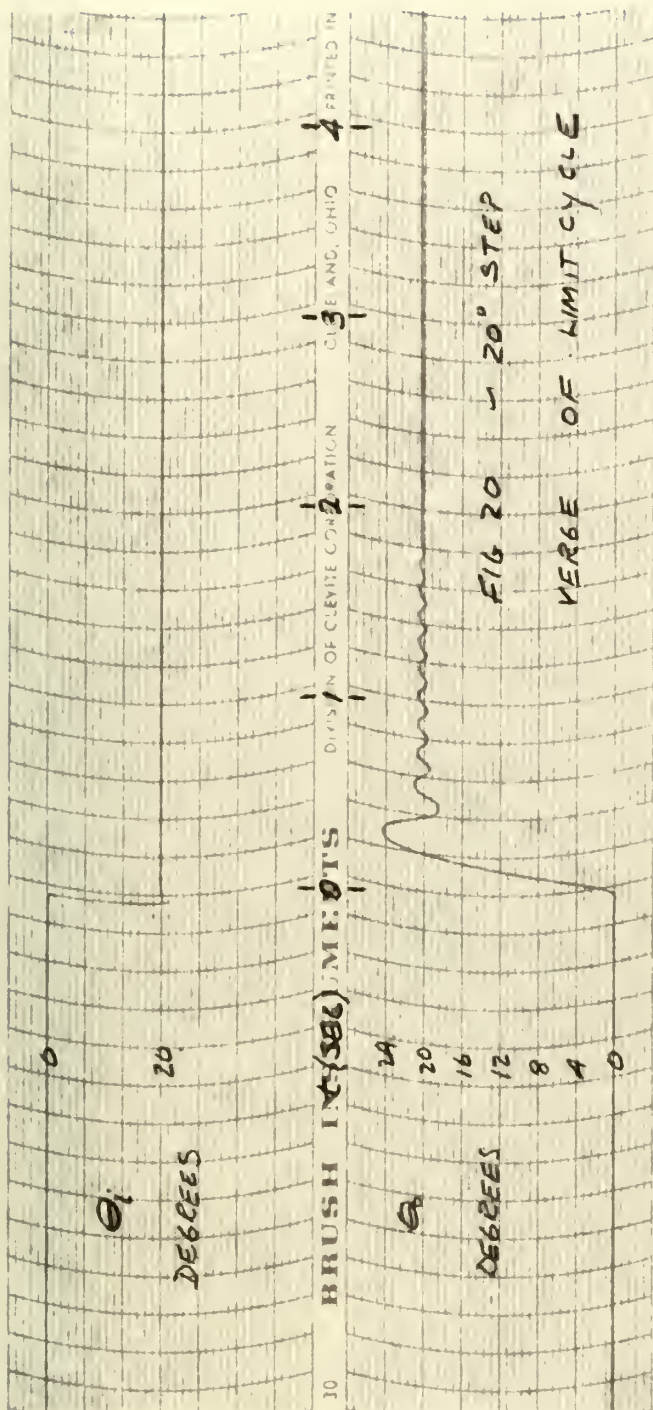
Operating with both the motor and tachometer generator in the gear train caused the system to have a break free torque about 25% of maximum torque. It was therefore desirable to examine the effect of reduced friction and damping by disconnecting the tachometer from the system. This reduced break free torque to about 10 percent of maximum torque.

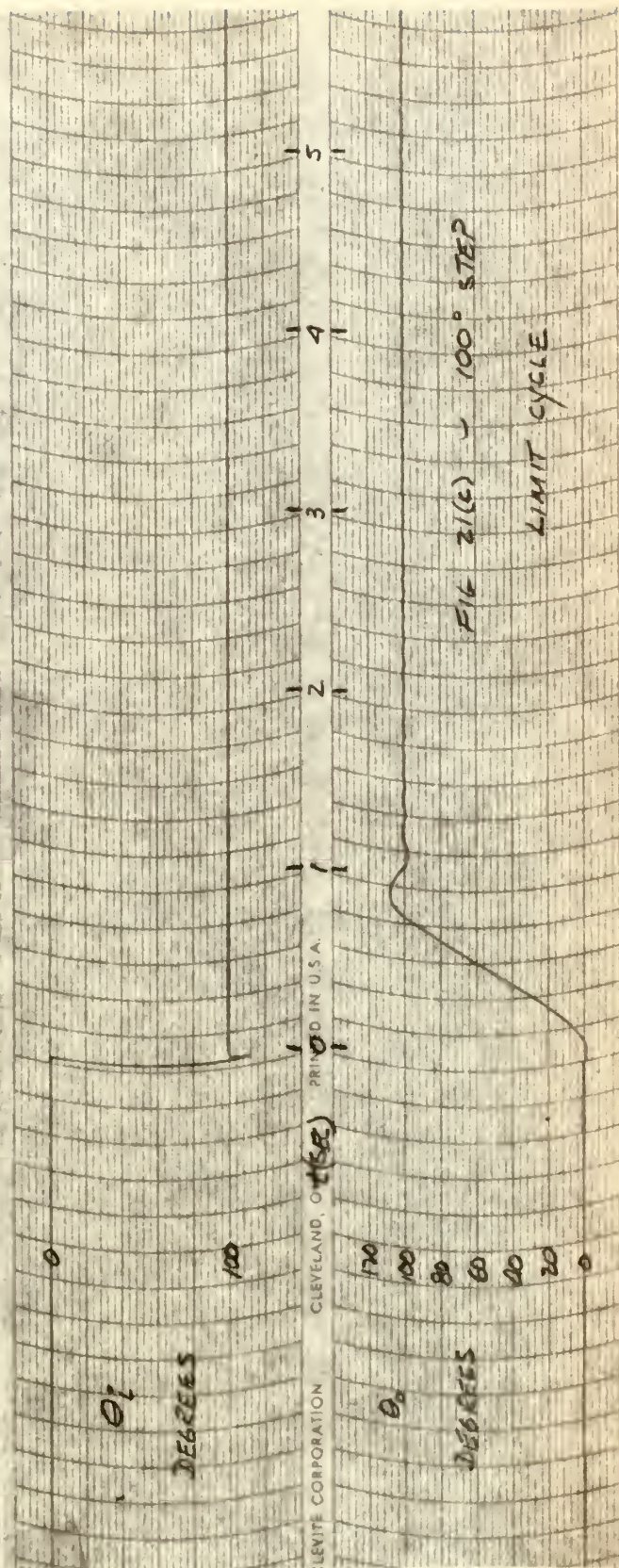
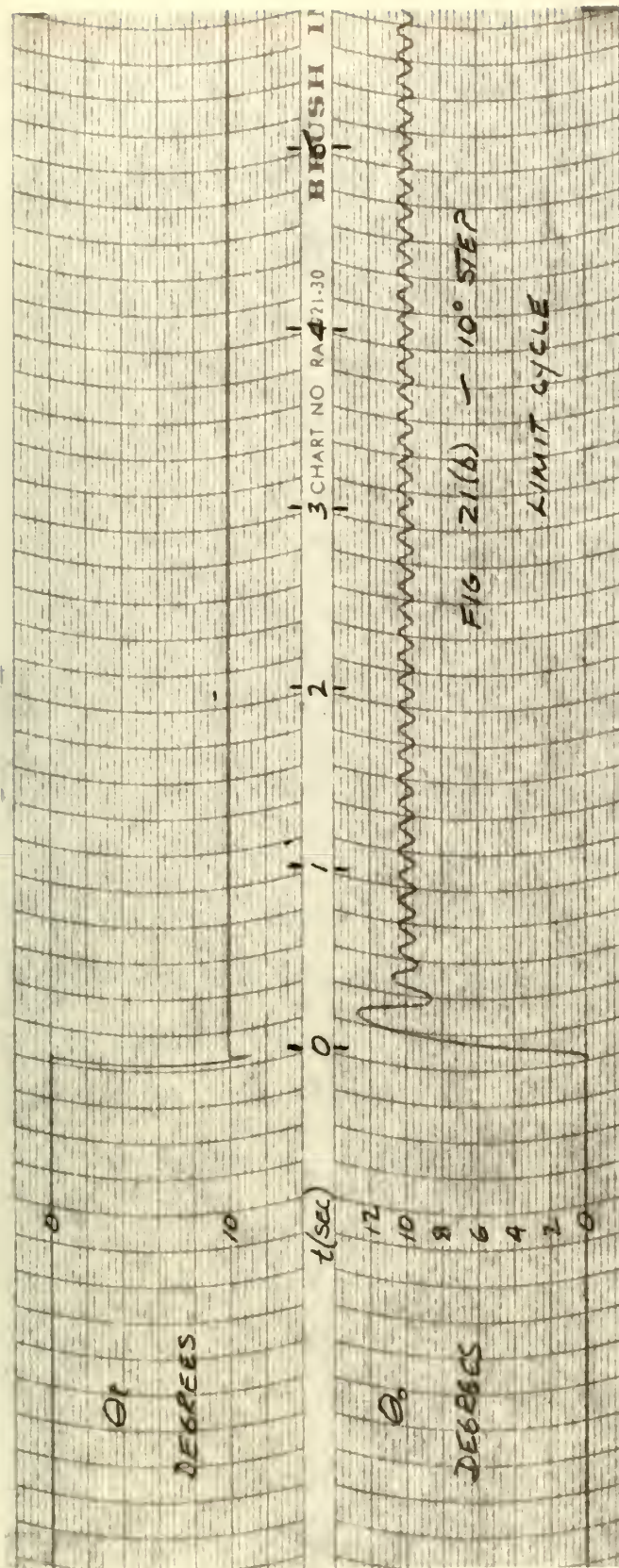
Fig. 19 shows system response to step inputs of 20, 40 and 60 degrees with K_p set at 8.4 volts/degree. At this low gain setting the system response is much the same as in the previous runs with no tachometer feedback. Oscillations are not of large magnitude nor do they persist long.

Fig. 20 shows the response to a 20 degree step with the gain constant set at 14.5 volts/degree. At this setting the system is on the verge of limit cycle operation in fact at this setting the servo sometimes would exhibit a limit cycle.

With a slight increase in K_p the system invariably would go into a limit cycle. The limit cycle existed regardless of the size of the step input (as long as the step was large enough to exceed the break free torque). Representative step inputs of 1, 10 and 100 degrees were recorded and are shown in Fig. 21. Each input results in limit cycle operation. The oscillations at the end of the 100 degree step are difficult to see on the tape because of the relative magnitude of the oscillation with respect to the scale necessary to show the step, but the oscillations exist.







No attempts were made to determine the cause(s) of the limit cycle. Theoretically, with the quasi-linear torque zone, it would seem that oscillations though extended should eventually damp out. At this potentiometer gain setting the width of the intermediate zone is approximately plus and minus three-tenths of a degree. From the first tape of Fig. 21, for the one degree step, the magnitude of the limit cycle is close to but not more than this same amount, three-tenths of a degree, therefore the servo should be oscillating entirely within the intermediate zone. There are of course other important non-linearities in the system, notably the backlash in the gear train which could be instrumental in causing the limit cycle. The amount of backlash in the gear train used in the experiment was not accurately measured due to mechanical problems. It was approximately one tenth of a degree.

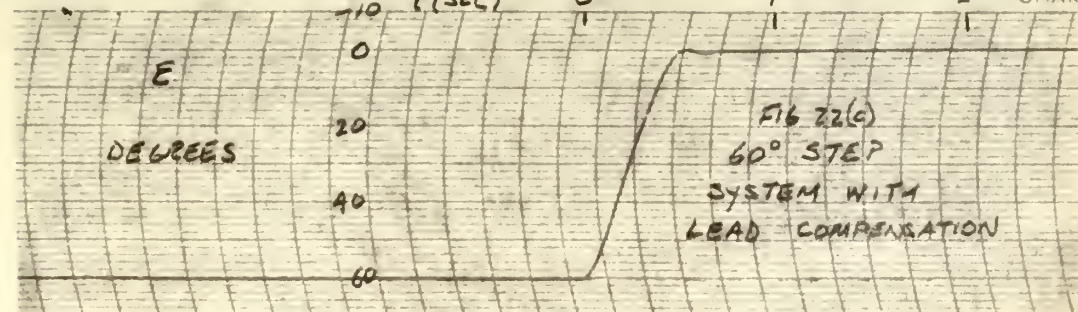
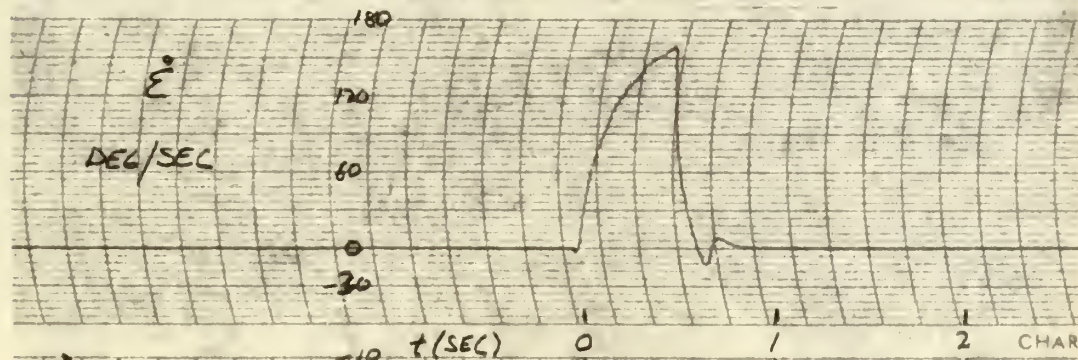
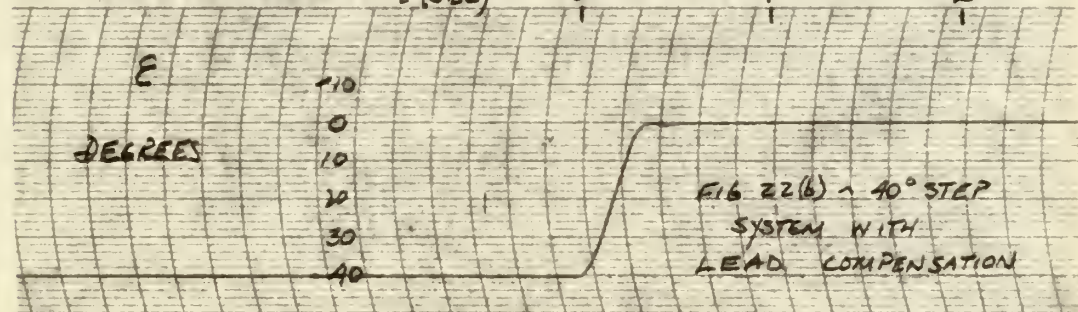
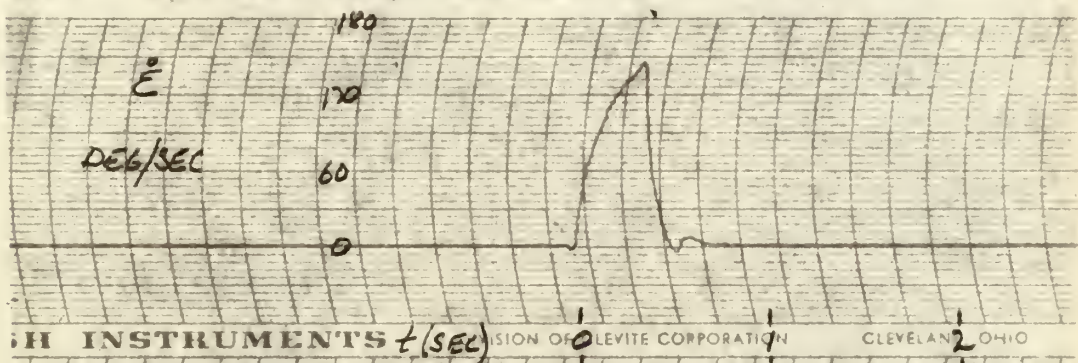
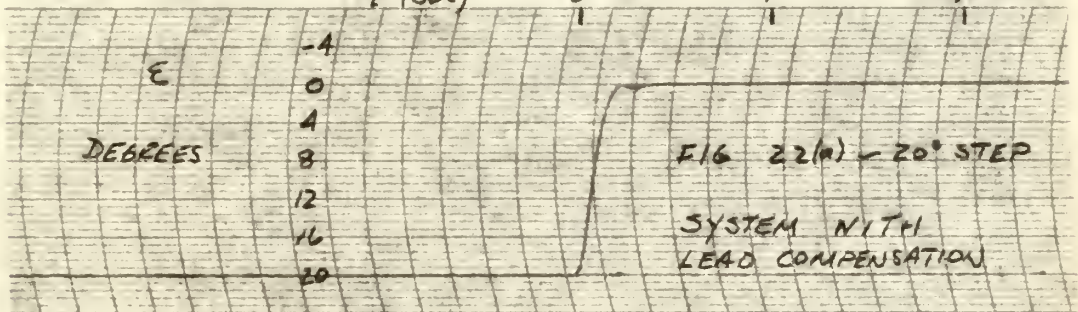
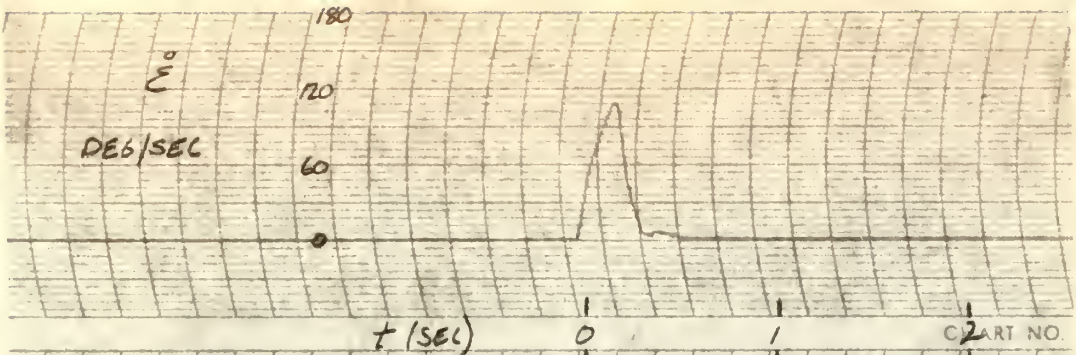
4) System Operation with Lead Network Compensation.

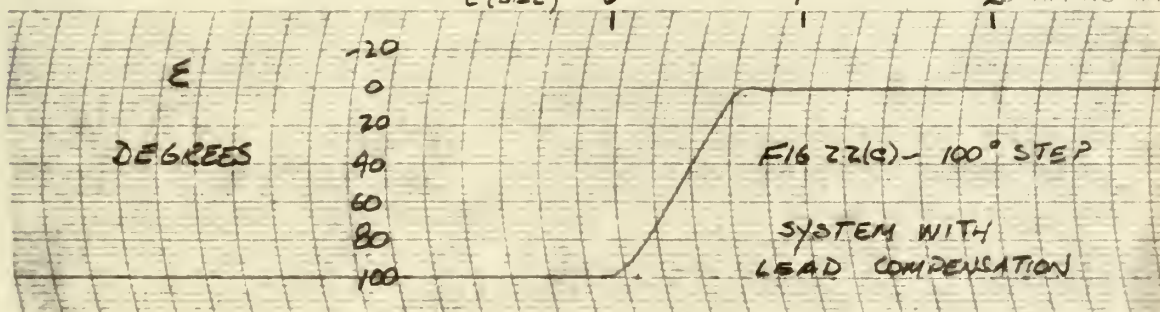
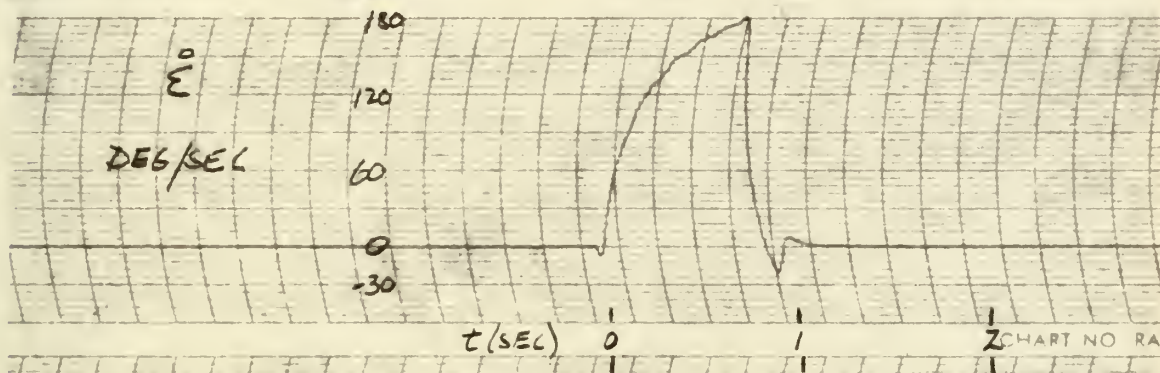
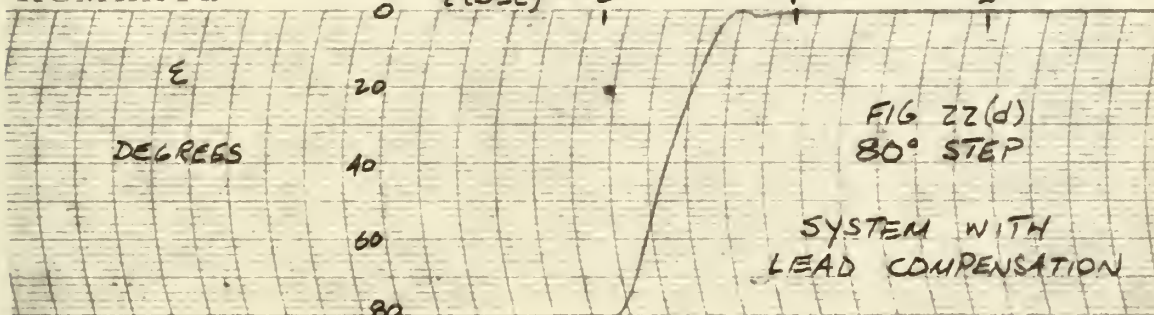
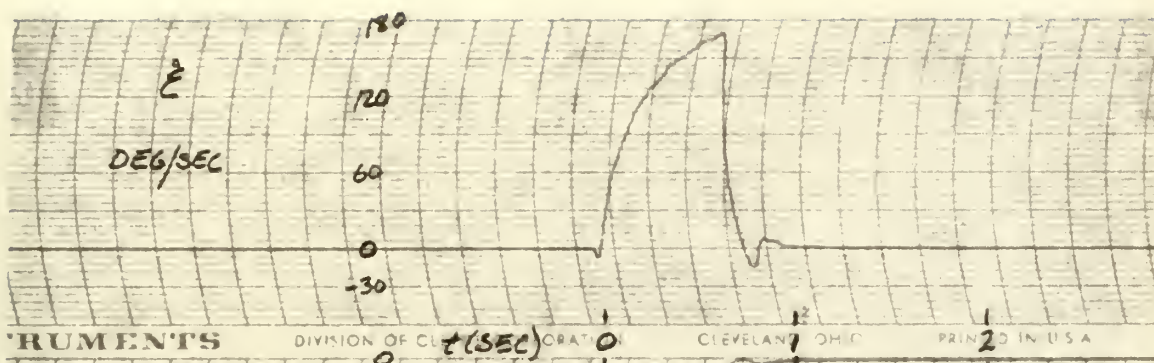
To provide an error rate signal to the servo amplifier with the tachometer disconnected a lead network was constructed. The composition of the network was the result of trial and error experimentation aimed at obtaining response. The transfer function of the network used was

$$(13) \quad \frac{e_o(s)}{e_i(s)} = \frac{5s}{.015s + 1}$$

Adjusting the lead network for no oscillation in response to a step input resulted in the system stepping in toward the zero error position; adjusting for no step in resulted in excessive oscillations, so that the transfer function given above was a compromise between the two extremes.

Response to steps of 20, 40, 60, 80 and 100 degrees is shown in Fig. 22(a) through (e). The gain constant was set at 8.4 volts/degree the same as for the tapes of Fig. 19. As before the final error cannot be determined from the tapes because of the scales necessary to depict the step itself.





The tapes of this series are shown primarily to indicate system response with small damping coefficient. Compared to the tapes made with tachometer feedback, the response of the lower friction, lower inertia system is more rapid even though, with the lower gain setting, the width of the intermediate zone is considerably larger than that previously used. As mentioned it was not possible to adjust this system for deadbeat response, and oscillations in the output position were present for all sizes of step input. It is not known whether these oscillations were caused by the lead network or by the small damping coefficient of the system. The oscillations all damped after no more than one cycle and appear, from the tapes, to tend toward the step-in rather than overshoot side of true deadbeat response. Because of this the oscillatory undershoot is more pronounced than any overshoot.

The recording of error rate in these tapes was obtained from another separate lead network and contains some discrepancies which, especially for the smaller steps, made an inaccurate recording of error rate. The difficulty is that the time constant of the recording lead network is not small enough with respect to the response time of the servo system itself. The effect of this can be best seen on the recording of the 20 degree step where the error rate does not change sign though the slope of the error itself does. In the succeeding, longer response curves this inaccuracy is not so pronounced.

Using the maximum value of K_p , the system with error rate control would not exhibit limit cycle operation. Oscillations persisted to a greater degree as gain was increased but decayed in a roughly exponential manner.

8) Criteria for Transistor Selection.

Certain electrical characteristics are important in determining the suitability of transistors for use as motor switching elements. These characteristics for the three transistors tested are given in Table II.

TABLE II

Transistor Electrical Characteristics

	2N155	2N554	2N618
P_c (Watts)	8.5	10	45
BV_{ce} (Volts)	-30	-40	-60
I_c (Amps)	-3	-3	-3
h_{fe} Min.	42 @ 0.5a	20 @ 0.5a	60 @ 1a
Power Gain	30 db	34 db	42 db

Fig. 6 showed measured curves of collector versus base current. These measurements were taken with the motor rotor blocked, hence the slope of a line from a point on the curve defines the current gain of a particular transistor at a particular value of collector (armature) starting current. Typical of the wide variation in transistor parameter values from those published is the current gain of the 2N155 and the 2N618. The 2N155 from the manufacturer's specifications is inferior to the 2N618 in this respect yet actually proved superior in the experiment and would, for the same values of K_a and K_p provide a smaller intermediate zone than the 2N618.

The collector leakage current I_{co} , the operating temperature and the allowable collector dissipation P_c are intimately related with regard to switch operation. I_{co} is a strong function of junction and

operating temperature. For maximum collector to emitter resistance ($\frac{V_{CE}}{I_C}$, switch off) it is necessary that I_{CO} be made as small as possible. At the normal extremes of switch operation, that is fully open or fully closed, the power dissipated in the collector is quite small. Typically, for the 2N155 driving the Oster motor with a 28 volt supply voltage, conditions are,

$$\text{Switch off - } V_{ce} = 28\text{v}, I_{CO} = .01\text{a}, P_C = .28\text{w}$$

$$\text{Switch on - } V_{ce} = 1.5\text{v}, I_C = 0.4\text{a}, P_C = .6\text{w}$$

Because of friction in the system it is possible for the motor to be at standstill in the dead zone with current in the armature circuit as large as that necessary to produce break away torque. For the system used in the experiment with the tachometer generator connected this current was as high as 0.22 amp. For this condition

$$V_{ce} = 25\text{v}, I_C = 0.22\text{a}, P_C = 5.5\text{w}$$

This value is approaching the rated power dissipation limit of the transistor operated with an adequate heat sink. Since the collector leakage current increases with temperature and thus with power dissipation, thermal runaway can occur which will destroy the switch. The rated power dissipation of the 2N155 is not great enough to insure against thermal runaway in this circuit.

BV_{ce} specifies the maximum voltage the transistor can sustain in the collector-emitter circuit. In transistor amplifier design it is common practice to employ a transistor with a voltage rating twice that of the maximum operating voltage. The 2N155 with a BV_{ce} rating of -30 volts was operated satisfactorily at a motor supply voltage of 28 volts, but this is not good practice. Since the transistors are switching inductive

loads it is to be expected that on switching the circuit off a voltage spike would be generated which could damage the switch. Evidence of spiking in the circuits tested was not found. This is probably because the collector-emitter resistance in the off condition is a relatively low resistance, typically thousands of ohms, and thus absorbs or effectively damps the surge and acts as a self-protection device in the circuit.

The input impedance of the transistor must be closely matched by the output impedance of the preceding amplifier stage. This is the purpose of the resistors R in the circuits of Figs. 2 and 4. Without proper impedance matching the leakage current is a regenerative mechanism, self-biasing the base increasing collector current thereby nullifying switching action. Since the input impedance of common emitter power amplifiers is low (30 ohms for the 2N155 for example) the preceding stage should be cathode follower, if vacuum tube powered, or common collector (emitter follower) if transistor powered.

From the considerations discussed above the 2N618, though not as favorable with respect to forward current gain as the 2N155 is the most desirable of the three transistors tested for switching the Oster motor. The 2N554, though capable of reliably handling the motor power, has too low a current gain to be of value.

9. Conclusions.

Transistor switches afford real, practical advantages over the use of magnetic relays in DC relay servo operation. Transistor switches are naturally suited to and afford dual mode operation.

The switching characteristic, current versus error or torque versus error is symmetrical about the null or zero error position. No hysteresis loop is present in the characteristic.

Magnetic relay contact arcing and mechanical failure is eliminated.

In the circuit tested a linear armature current versus error relationship was obtained over a large range of potentiometer gain constant. When used to switch a shunt motor this would afford a linear torque versus error switching region followed by a torque saturated region. Width of the linear zone is adjustable through the choice of transistors, i.e. forward current gain, the potentiometer gain or the amplifier gain.

When switching the series motor a dead zone, dependent upon definition exists. The width of the dead zone and of the essentially linear zone of operation between dead zone and torque saturation is adjustable as for the shunt motor.

10. Recommendations.

It has been shown that transistor switching is an effective means of controlling DC motor relay servos. It is apparent that transistors as well as other semi-conductor devices will have important applications in the field of feedback control systems. As an extension of the scope of this study it is recommended that;

1. The application of transistor switching to AC servomotor control be studied;
2. The shunt motor switching circuits shown in this study be tested and evaluated; and
3. A design project be undertaken to transistorize the entire servo system.

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